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LIGHTNING PROTECTION OF STRUCTURES & ELECTRICAL EQUIPMENT

A dissertation submitted in partial fulfillment of registration for the award of the M.Sc. Degree

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بسم الله الرحمن الرحيم

أَوْ كَصَيِّبٍ مِّنَ السَّمَاءِ فِيهِ ظُلُمَاتٌ وَرَعْدٌ وَبَرْقٌ يَجْعَلُونَ أَصَابِعَهُمْ فِي آذَانِهِم مِّنَ الصَّوَاعِقِ
حَذَرَ الْمَوْتِ وَاللَّهُ مُحِيطٌ بِالْكَافِرِينَ
يَكَادُ الْبَرْقُ يَخْطَفُ أَبْصَارَهُمْ كُلَّمَا أَضَاءَ لَهُم مَّشَوْا فِيهِ وَإِذَا أَظْلَمَ عَلَيْهِمْ قَامُوا وَلَوْ شَاءَ اللَّهُ
لَذَهَبَ بِسَمْعِهِمْ وَأَبْصَارِهِمْ إِنَّ اللَّهَ عَلَى كُلِّ شَيْءٍ قَدِيرٌ

صدق الله العظيم

البقرة آية (20, 19)

وَيُسَبِّحُ الرَّعْدُ بِحَمْدِهِ وَالْمَلَائِكَةُ مِنْ خِيفَتِهِ وَيُرْسِلُ الصَّوَاعِقَ فَيُصِيبُ بِهَا مَن يَشَاءُ وَهُمْ
يُجَادِلُونَ فِي اللَّهِ وَهُوَ شَدِيدُ الْمِحَالِ

صدق الله العظيم

الرعد آية (13)

الإهداء

إلى الوالد العزيز
إلى روح الوالدة العزيزة
إلى اخوتي وأخواتي
إلى الزوجة العزيزة والأبناء
إلى كل باحث فى هذا المجال

الصادق

DIDICATION

To my dear father

To the soul of my dear mother

To my brothers & my sisters

To my wife & my sons

To every one who researches in this field

ELSADIG

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Finally, deepest appreciation goes to all for their compliments.

الملخص

تستخدم نظم الحماية من الصواعق لمنع الأضرار التى تلحق بالمباني ومحتوياتها والتجهـيزات الكهربائية من الصواعق والتأثيرات المناوئة لها. والغرض الأساسي من هذا البحث هو:

- دراسـة طبيعة البرق والصواعق وتأثيراتها المدمرة على المباني والتجهيزات الكهربائية.
- مناقشة نظم الحماية من الصواعق للمباني والتجهيزات الكهربائية.
- تصميم نظام حماية من الصواعق لمبنى متعدد الطوابق.

ABSTRACT

Lightning protection systems are used to prevent damage to structures and protect its occupants and equipment from the effects associated with lightning strokes.

Protective devices are also used to prevent the resulting induce voltages and travelling waves from affecting the electrical equipment.

The main purpose of this dissertation is to:

- Study the nature of lightning and its destructive effects on structures and electrical equipment.

- Discuss the protection systems for structures and electrical equipment against direct lightning strokes and induced overvoltages.

- Design a lightning protection system for a tall building.

CONTENTS

Chapter 1

1 Introduction

It is essential for electrical power engineers to reduce the number of outages and preserve the continuity of service and electric supply. Therefore, it is necessary to direct special attention towards the protection of transmission lines and power apparatus from the chief causes of overvoltages in electric systems, namely lightning overvoltages and switching overvoltages.

Also attention towards the protection of structures and its contents, against lightning and induced overvoltages is the responsibility of electrical power engineers.

For the study of overvoltages a basic knowledge of the origin of overvoltages, surge phenomenon, and its propagation is desirable.

Lightning phenomenon is a peak discharge in which charge accumulated in the cloud discharges into a neighboring cloud or to the ground. To prevent the effect of these huge discharges towards the earth, a lightning protection system should be adopted.

Lightning protection systems are the modern development of the innovation pioneered by Benjamin Franklin (the lightning rod). Today, lightning protection systems are used on thousands of buildings, homes, factories, towers and even in space.

The main purpose of a lightning protection scheme is to shield a building, its occupants and equipment from the adverse effects associated with a lightning strike.

To perform correctly, the protection scheme must capture the lightning, lead it safely downwards and then disperse the energy within the ground. The components used to facilitate this are air termination, down leads, bonding leads and the earth termination (or electrode).

Without a designated path to reach ground, a lightning strike may choose to utilize any conductor available in side a building. This may include telephone cables, electrical lines, water or gas pipes or the structure itself.

As a result, lightning presents several hazards to any structure such as fire, side flashes, damage to building materials and damage to appliances.

Adding a protection system doesn't prevent a strike, but gives it a better, safer path to ground. The air terminals, cables and ground rods work together to carry the immense currents away from the structure, preventing fire and most appliances damage.

Surge protectors provide some degree of protection from voltage spikes from everyday power surges and distant lightning strikes. But when lightning strikes a structure directly or very close to it, these devices will not guarantee protection.

Not even a full lightning protection system with rods, cables and grounds will guarantee against the damage of structures, electrical equipment, electronics and computers.

For any system to provide 100% protection, it must divert almost 100% of the lightning current from a direct strike, which is nearly physically impossible. (Ohm's law states that for a set of resistances connected in parallel, the current will be distributed across all resistances, at levels inversely proportional to the different values of resistance).

A building is nothing more than a set of resistors 'connected' in parallel- the electrical wiring, plumbing, phone lines, steel framework, etc. In a direct lightning strike, the current will not follow only one path- it will distribute itself across all paths to ground depending on each path resistance.

Lightning current often peaks at 100,000 or more Amperes. With that in mind, consider if you have a lightning protection system installed, and your house is hit directly by lightning. If the protection system takes even 99.9% of the current, then your electrical wiring may take the remaining 0.1%. 0.1% of 100,000 Amperes is a 100 Amps surge through your lines- that may be enough to take out your computer.

To ensure that the electrical equipment is capable of withstanding the overvoltages that are met with in the service, a well-equipped lightning simulation and test laboratories for power frequency voltage test, impulse voltage and impulse currents test are necessary.

A surge or lightning protection system may not be fully satisfactory, but any protection device within the system, will provide some degree of protection from everyday line spikes and distant lightning strikes.

The best, and cheapest, way to protect your television, computer, or any electronic appliances is to unplug all power, telephone (modem), and antenna connections during a thunderstorm.

Chapter 2

2 The nature of Lightning

2.1 Lightning History

Early cultures relied on myth and magic to explain lightning and to ease their fears. The ancient Greeks, for example, believed that the king of all gods, Zeus, threw lightning down from the heavens to show his anger at the people below. Lightning was his weapon.

As the study of weather science progressed, people stopped thinking of lightning as a punishment from the gods. It was not until 1700s, that scientists really began to understand lightning.

Benjamin Franklin was one of the first lightning scientists. In 1752, he performed his legendary kite experiment. During a thunderstorm, he tied a metal key to the end of a kite string and set his kite flying in the storm's winds. When sparks jumped from the electrified key, he knew that electrical current had traveled from electrified air above down the kite string to his key. He had suspected that lightning was actually a natural form of electricity. With the experiment, he was able to conclude that lightning was an electrical current.

In the years that followed, scientists learned more and more about lightning. Although there is no completely safe way to avoid lightning strike, scientists tested theories to provide some protection. Modern lightning research began on the later part of the nineteenth century.

In the 1970s, meteorologists and other scientists developed lightning detection networks. Today, they can track lightning strikes all over the country using the National Lightning Detector Network which uses magnetic sensors and computers to detect when and where lightning strikes the ground. Lightning data is instantly provided to meteorologists for analysis.

Lightning is still frightening because of its ferocious power. Lightning is classified as plasma, the fourth state of matter.

In this chapter we shall briefly survey the information available concerning lightning. The intent of the survey will be to give a general picture of the overall phenomenon of lightning and its destructive effects. This general picture will serve as the background of the lightning discharge on electrical equipment and structures.

Lightning can be defined as a transient, high-current electric discharge whose path length is generally measured in kilometers (the electrode separation, i.e. cloud to cloud or cloud to ground is very large, perhaps 10 km or more).

Lightning occurs when some region of the atmosphere attains an electric charge sufficiently large that the electric fields associated with the charge cause electrical breakdown of the air. The most common producer of lightning is the thundercloud, however, lightning also occurs in snowstorms, sandstorm, and in the cloud over erupting volcanos.

The mechanism of charge formation in the cloud and their discharges are quite a complicated and uncertain process. Nevertheless, a lot of information has been collected since the last fifty years and several theories have been put forth for explaining the phenomenon.

2.2 Charge Formation in the Clouds

The factors that contribute the formation or accumulation of charge in the clouds are too many and uncertain. But during thunderstorms, the heavy air currents separate positive and negative charges with ice crystals in the upper part and rain in the lower part of the cloud. This charge separation depends on the height of the cloud, which range from 200 to 10,000 m, with their charge centers probably at a distance of about 300 to 2000 m. The volumes of the cloud that participate in lightning flashover are uncertain, but the charge inside the cloud may be as high as 1 to 100 coulombs. Clouds may have a potential as high as 10^7 to 10^8 V with field gradient ranging from 100 V/cm within the cloud to as high as 10 kV/cm at the initial discharge point. The energies associated with the cloud discharges can be as high as 250 kWh.

It is believed that the upper region of the cloud are usually positively charged, whereas the lower region and the base are predominantly negative except the local region, near the base and the head, which is positive.

The maximum gradient reached at the ground level may be as high as 300 V/cm, while the fair weather gradients are about 1 V/cm. A probable charge distribution model is given in (fig. 2.1) with the corresponding field gradients near the ground.

According to the Simpson's theory (fig. 2.2) there are three essential regions in the cloud to be considered for charge formation.

Below region A, air travel above 800 cm/s, and no raindrops all through.

In region A, air velocity is high enough to break the falling rain drops causing a positive charge spray in the cloud and negative charge in the air. Region A, eventually becomes predominately positively charged while region B above it becomes negatively charged by air currents. In the upper region in the cloud, the temperature is low (below freezing point) and only ice crystals exist.

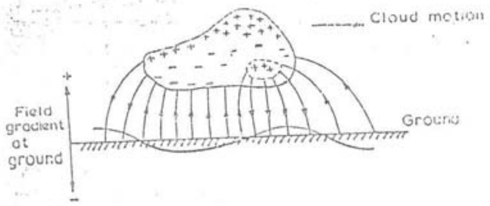

Fig 2.1 Probable field gradient near the ground corresponding to the probable charge distribution in a cloud

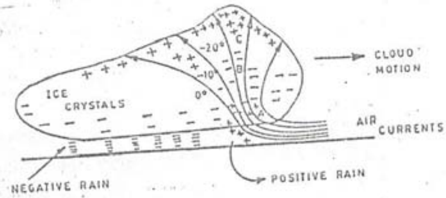

Fig 2.2 Cloud model according to Simpsons's theory

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The distribution of the charge within the cloud becomes as shown in (fig. 2.2).

However, the above theory is obsolete and the explanation presented is not satisfactory. Recently, Reynolds and Mason proposed modification, according to which the thunder clouds are developed at 1 to 2 km above the ground level and may be extended up to 12 to 14 km above the ground. For thunder clouds and charge formation air currents, moisture and specific temperature range are required.

The air currents controlled by the temperature gradient move upward carrying moisture and water droplets. The temperature is 0 C^o at about 4 km from the ground and may reach – 50 C^o at about 12-km height. Water droplets freeze at – 40C^o as solid particles on which crystalline ice patterns develop and grow the effective freezing temperature range are around – 33 C^o to – 40 C^o.

The water droplets in the thunder cloud are blown up by air currents and get super cooled over a range of height and temperature. When such freezing occurs, the crystals grow into large masses and due to their weight and gravitational force start moving downwards. Thus, a thunder cloud consists of super cooled water droplets moving upwards and large hail stone moving downwards. When the process of cooling extends to inside warmer water in the core, it expands, thereby splintering and spraying the frozen ice shell. The splinters being fine in size are moved up by the air currents and carry a net positive charge to the upper region of the cloud. The hail stone that travel downwards carry an equivalent negative charge to the lower regions of the cloud and thus negative charge builds up in the bottom side of the cloud.

According to Mason, the ice splinters should carry only positive charge upwards. Water being ionic in nature has concentration of H^- and OH^+ ions. The H^- are much lighter, they diffuse much faster all over the volume. Therefore, the lower portion, which is warmer, will have a net negative charge density, and hence the upper portion, i.e. cooled region will have a net positive charge density. Hence, it must be appreciated that the outer shells of the frozen water droplets coming into contact with hailstones will be relatively cooler and therefore acquire a net positive charge.

According to the Reynold's theory, which base on experimental results, the hail packets get negatively charged when impinged upon by warmer ice crystals. When the temperature conditions are reversed, the charging polarity reverses. However, the extent of charging and consequently the rate of charge generation were found to disagree with the practical observations relating to thunder clouds.

Rate of Charging of Thunder Clouds

Mason considered that thunderclouds consist of a uniform mixture of positive and negative charges, which separate vertically due to hail stones and air currents. If λ is a factor, which depends on the conductivity of the medium, there will be resistive leakage of charge from the electric field built up.

Let E be the electric field intensity, v the velocity of separation of charges, and ρ the charge density in the cloud. Then the electric field intensity E is given by:

$$dE/dt + \lambda E = \rho v \qquad (2.1)$$

Hence
$$E = (\rho v / \lambda) [1 - \exp(-\lambda t)] \qquad (2.2)$$

At the start of charge separation, the equation assumes initially $E = 0$ at $t = 0$.

Let Qs be the separated charge and Qg be the generated charge, then;

$$\rho = Qg / Ah \qquad (2.3)$$

$$E = Qs / A\epsilon o \qquad (2.4)$$

Where ϵo is the permitivity of the medium, A is the cloud area and h is the height of the charge region.

From equation (2.2), on substitution;

$$Qg = \frac{Qs\, h}{v[1 - \exp(-\lambda t)]} = \frac{M}{v[1 - \exp(-\lambda t)]} \qquad (2.5)$$

Where M = Qs h = the electric moment of the thunder-storm.

The average values observed for thunderclouds are:

Time constant = $1/\lambda$ = 20s
Electric moment M = 110 c-km and
Time for first lightning flash to appear, t = 20s.
The velocity of separation of charges, v = 10 to 20 m/s.

Substituting these values, we get:

$$Qg = \frac{20{,}000}{20}\ \text{C} = 1000\ \text{C for } v = 20\ \text{m/s.}$$

2.3 Types of Lightning Discharge

Much information on lightning has been obtained from photographs taken with a preliminary opened objective lens. It is important however, that no other bright light source should be present within the vision field of the camera lens. The film can then be exposed for many minutes until the spark finds its way into the frame. After this, the lens should be closed with the shutter and the camera should be set ready for another shot.

Lightning discharges can be classified, photography, into two groups, intercloud discharge and ground strikes. The frequency of the former is two or three times higher than that of the latter. An intercloud spark is never a straight line, but rather has numerous bends and branching. Normally, the spark channel is as long as several kilometers.

The length of lightning spark that strikes the ground can be defined more exactly. The average cloud altitude may close to three kilometers. Sparks channels have the same average length. Of course, this parameter is statistically variable, because a discharge from a charged cloud center may start at any altitude up to 10 km and because of large number of spark bends. The latter are observable even with the unaided eye. In a photograph, they may look strikingly fanciful (fig.2.3). The photograph shows that the main bright spark reaching the ground has numerous branches, which have stopped their development at various altitudes. A single branch may have a length comparable with that of the principal spark channel (fig. 2.4).

Branches can be conveniently used to define the direction of lightning propagation. Like a tree, a lightning spark branches in the direction of growth. In addition to descending sparks outgrowing from a cloud toward the ground, there are also ascending sparks from a ground construction and developing up to a cloud (fig. 2.5). Their direction of growth is well indicated by branches diverging upward.

In a flat country, an ascending spark can arise only from a skyscraper or a tower of at least 100 ~ 200m high and a number of ascending sparks grow with the building height. In mountain regions, ascending sparks have been observed from much lower buildings.

2.4 Mechanism of Lightning Strokes

To have a clear idea about the lightning stroke occurrence, visualization of the mechanism of lightning is helpful. This is regarded to consist of four rather distinct stages. Although it is recognized that these several stages may overlap and proceed simultaneously. The four stages are indicated in (fig 2.6).

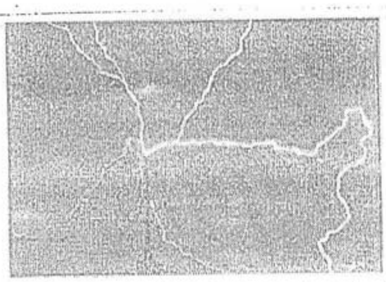

Fig. 2.3

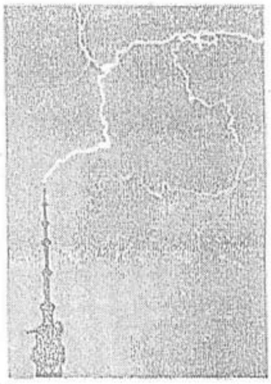

Fig 2.4

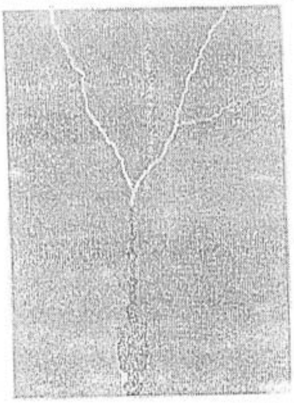

Fig 2.5

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1. The first stage consists of the formation and charging of a thundercloud.

   As discussed before, the distribution of charge depends upon the whims of the air currents, resulting in positive charges in the top portions of the cloud, while the bottom portions are negatively charged except for a local concentration of positive charges at the lower front of the clouds. The exact process by which the cloud becomes charged is a matter of conjecture.

2. The second stage comprises the formation of local discharges between adjacent regions in the cloud. The net effect of which is to equalize the potential in the vicinity and increase the ionization, so the subsequent streamers may penetrate with great ease, thus making available a larger reservoir of charge to the lightning stroke.

3. The third stage involves the propagation of a stepped leader towards earth, blazing an ionized path up which the main stroke may proceed. As the stepped leader makes its way downward by a series of short thrusts, it branches out in different directions at various points along its route, and its whole path acquires a charge from the cloud above. The ultimate contact with ground is equivalent to the contact of a charged conductor having definite surge impedance. Thus upon contact all the facilities exist for the propagation up the channel of a wave of opposite polarity. Since the lightning channel is in air it might be expected that the velocity of propagation of the main stroke up the channel would be the velocity of light. However, the additional capacitance added by the numerous branches would tend to decrease this velocity.

4. The fourth stage follows the elimination of the surge impedance of a lightning stroke and the completion of the discharge paths in the cloud mass.

   If the potential at the point of rupture falls to such a low value, owing either to the failure of cloud streamers to extend the area of discharge, or to the high resistance of these streamers. Then the main discharge may die out or be reduced to a comparatively feeble residual current. The drop in potential at the point of rupture then invites discharges from other portions of the cloud, which will build up local charges and potentials to such values as will precipitate as repeated strokes. A continuous leader rather than stepped leader characterizes this stroke, since a polarity ionized path already exists.

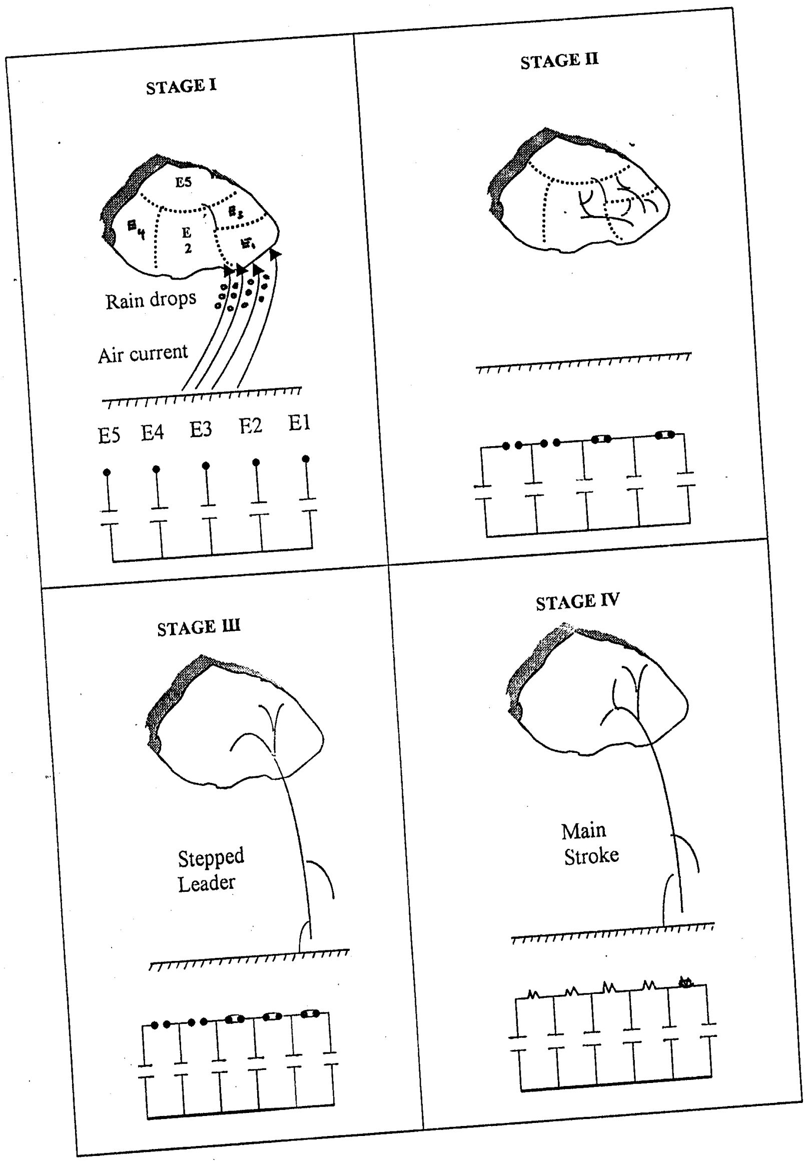
STAGE I
E5
E4
E2
E3
E1
Rain drops
Air current
E5 E4 E3 E2 E1
STAGE II
STAGE III
Stepped
Leader
STAGE IV
Main
Stroke

Fig. (2.6)

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2.5 The 'Rolling Sphere' Concept

Given the lightning process already described, it is logical to assume that a lightning strike terminates on the ground (or on the structures) at the point where the upward streamer was originally launched.

These streamers are launched at points of greatest electric field intensity and can move in any direction towards the approaching downward leader. It is for this reason that lightning can strike the side of a tall structure rather than its highest point.

The position of the greatest field intensity on the ground and on the structure will be at those points nearest to the downward leader prior to the last step. The distance of the last step is termed the striking distance and is determined by the amplitude of the lightning current. A sphere of radius equal to the striking distance can represent this striking distance.

The Rolling sphere concept is a simple means of identifying areas that need protection, taking into account the possibility of side strikes on the structures.

2.6 Parameters and Characteristics of the Lightning Strokes

The parameters and characteristics of lightning include the amplitude of the currents, the rate of rise, the probability distribution of the above and the waveshapes of the lightning voltages and currents.

Lightning currents are usually measured either directly from high towers or buildings or from the transmission tower legs. Measurements made by several investigators and committees indicated that large strokes of currents (> 100kA) are possible.

Other important characteristics are time to peak value and rates of rise. From the field data, it was indicated that 50% of lightning currents have a rate of rise greater than 7.5 kA /μs, and for 10 % strokes it exceeds 25 kA /μs.

Measurements of surge voltages indicate that a maximum voltage, as high as 5,000 kV, is possible on transmission lines, but on the average, most of the lightning strokes give rise to voltage surges less than 1000 kV on lines. The time to front of these waves varies from 2 to 10 μs and tail times usually vary from 20 to 100 μs. The rate of rise of voltage, during rising of the wave may be typically about 1 MV/μs.

2.7 Mathematical Model for Lightning

During the charge formation process, the cloud may be considered to be a non-conductor. Hence, various potentials may be assumed at different parts of the cloud. If the charging process is continued, it is probable that the gradient at certain parts of the charged region may exceed the breakdown strength of the air or moist air in the cloud. These local discharges may finally lead to a situation where a large reservoir of charge involving a considerable mass of cloud hangs over the ground, with the air between the cloud and the ground as a dielectric.

When a streamer discharges to the ground during the first stroke, followed by the main stroke with considerable currents flowing, the lightning stroke may be thought of as a current source of value Io with source impedance Zo dischgarged to earth. If the stroke strikes an object of impedance Z, the voltage built across it may taken as:

$$V = IZ$$

$$= Io \frac{ZZo}{Z + Zo} \tag{2.6}$$

$$= Io \frac{Z}{1 + Z / Zo} \tag{2.7}$$

The source impedance of the lightning channels is not known exactly, but it is estimated to be about 1000 to 3000 Ω. The objects of interest to electrical engineers, namely, transmission lines etc. have surge impedances less than 500 Ω (*overhead lines 300 to 500 Ω, ground wires 100 to 150 Ω, etc.*).

Therefore, the value Z/Z*o* will usually be less than 0.1 and hence can be neglegted. Hence , the voltage rise of lines may be taken to be approximately $V = Io\,Z$, where I*o* is the lightning stroke current and Z the line surge impedance.

If a lightning stroke current as low as 10,000A strikes a line of 400 Ω surge impedance, it may cause an overvoltage of 4000 kV. This is a heavy overvoltage and causes immediate flashover of the line conductor through its insulator strings.

In case of a direct stroke occuring over the top of an unshielded transmission line, the current wave tries to divide into two branches and travels on either side of the line. Hence, the effective surge impedance of the line as seen by the wave is Zo/2 and taking the above example, the overvoltage caused may be only 10000 x (400/2) = 2000 kV. If this line were to be a 132 kV line with an eleven 10- inch disc insulator string the flashover of the insulator string will take place, as the impulse flshover voltage of the string is about 950 kV for a 2 μs front impulse wave.

2.8 **Effects and Damage Caused by Lightning**

Lightning is nothing more than a long spark. However, it is estimated that about 2,000 storms exist at any on time in the world hurling 30 to 100 flashes to the ground every second. If these estimations are correct, then each year over 3 billion lightning strokes bombard the earth.
Lightning causes damage, death and injury as explained below.

2.8.1 Direct lightning Strokes

When a thunder directly discharges on a transmission line or tower it is called a direct stroke. This is the most severe form of stroke. Overvoltages occur due to these discharges and are most harmful when they are in the order of several million volts; the insulator flashes over, punctures and gets shattered. The wave travels to both sides shattering line insulators until the surge is dissipated sufficiently. The waves reach the sub-station and produce stresses on equipment insulators.

When a direct lightning stroke occurs on a tower, the tower has to carry huge impulse currents. If the tower footing resistance is considerable, the potential of the tower rises to a large value with respect to the line and consequently a flashover may take place along the insulator strings. This is known as back flashover.

These strokes are protected by earth wires laid parallel to the main conductors of the transmission lines and supported on the same towers and earthed at every tower footing.

Atypical 100 MV lightning flash can heat the air more than 40,000 degrees, which causes it to expand and then contracts as it cools. So the effect of a direct strike to a person needs no explanation. The victim can suffer heart failure; brain damage; suspension of breathing or paralysis as well as many other medical effects, including burns.

2.8.2 Induced Lightning Strokes

Remote lightning strikes may affect buildings and may induce high voltages into medium and low voltage overhead lines feeding the building.

Due to the strong electromagnetic fields set up by lightning, overvoltages are induced into the overhead lines. This is caused by sudden changes in the magnitude of the field existing between the cloud and the ground surface, with the result that free charges flow through the overhead lines producing travelling waves.

The danger from induced sparks arises with the presence of explosive gas mixtures, readily ignitable materials, etc.

2.8.3 Structural Damage

The principal effects of lightning discharge to a structure are electrical, thermal and mechanical. These effects are determined by the currents, which are discharged into the structure. These currents are unidirectional with amplitudes varying from a few hundreds to a maximum of 200kA, with a statistical average of 20kA.

Buildings hit by lightning often catch fire; the resulting smoke and flames are obvious hazards.

The fast rise and large peak amplitude can produce severe mechanical effects. Current magnitudes can rang from around 3kA to 200kA.

Long duration currents can cause fire, whilst short duration high current peaks tend to tear or bend metal parts. The electromagnetic force developed is proportional to the square of the instantaneous current. Because of these mechanical forces, it is necessary that lightning conductor systems be safely fastened to the building, which is intended to be protected.

When lightning strikes an unprotected building the stroke seeks the lowest impedance path to earth which is normally through the electrical wiring or water pipes. In order to reach these metal paths the discharge must pass through some type of barriers. In penetrating such barriers, explosive damage usually results. The explosive effect can dislodge materials with considerable force sufficient to hurl relatively large pieces of masonary or wood many meters away.

2.8.4 Side-Flashing

The problems relating to side flashing have attracted a great deal of attention in recent years and due consideration is given when designing a lightning protection system. Damage to life and property can occur if the danger of side flashing is not considered.

The principles of side flash can be explained by the following example, (fig.2.7).

If the lightning protection system on a structure is hit by lightning, then the current flowing through the system and the resistance / impedance offered by the conductor path will determine the magnitude of the potential difference seen by the lightning conductors with respect to true earth. The lightning conductor can, instantaneously, have a potential of magnitude of megavolts (1,000,000) with respect to true earth.

If there is metal work in close proximity to the lightning conductors, which are connected directly to earth, then for the purpose of this example, we can say that it is at zero volts with respect to true earth.

If the current, flowing down the lightning conductor path, at the time of discharge sees high impedance along route and the nearby metal work offers a lower impedance path to earth, then the discharge will flash over to the nearby network, provided the magnitude of the potential difference is sufficient to breakdown the gap ‘D’.

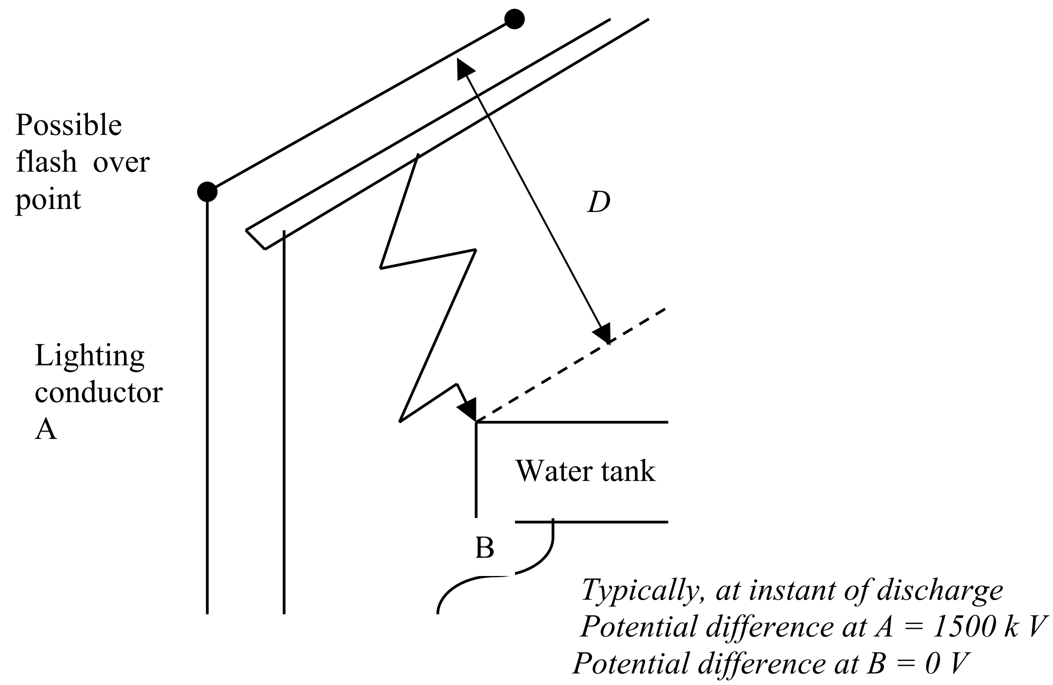


Fig. (2.7) Example of side flashing

Some of the reasons why side flashing could occur include:

1. Faulty lightning protection system:
   A faulty lightning protection system may well have an interruption in its electrical path, thus when the discharge occurs, it prefers to travel down a nearby earth path which offers a lower impedance.
2. Incorrect routing of conductors:
   A good lightning protection system should always follow the most direct route to earth. Unfortunately, practical considerations do not always allow this.
3. High impedance of lightning protection system:
   A high resistance in the lightning protection conductors can easily be caused by one poor electrical joint within the system, badly designed clamp, an incorrect installation fitting, or inferior quality corroded materials can be sufficient to cause a high resistance spot.

Chapter 3

3 Protection of Structures against Lightning

When structures are struck by lightning, electrical, mechanical and thermal effects are caused by the huge momentary discharges of lightning strokes.

The momentary discharges raise the potential of the protection system with respect to the true earth to high value. It may also produce around the earthing electrode a high gradient, which can be dangerous to persons and to livestock.

As the rate of rise of the lightning current is very high ~ 10,000 A/μ sec. It may be considered as a high frequency current which causes an inductive voltage drop across the vertical lightning conductor (inductance ~ 19×10^{-5} H/100m) which has to be added to the ohmic voltage drop across the earthing system.

Water pipes, electrical installation cables and other metal works, long section of it, are buried in the ground, which are not connected or inductively coupled to the lightning conductors system, remain at true earth potential throughout the lightning process.

As the lightning protection system may be raised to a high potential with respect to true earth, there is a risk of flashover to the metal or to the structure.

Thermal effects are confined to temperature rise of the lightning protection system through which the lightning current passes and are negligible because the duration of the lightning current is very short (μ sec.).

Where a high electric current is discharged through parallel conductors in close proximity, these are subjected to large mechanical forces. Secure mechanical fixing is therefore required for lightning conductors.

Another mechanical effect associated with lightning discharge is due to the fact that the air channel (i, e. between the thunder cloud and the lightning conductors) along which the discharge propagates, is suddenly raised to a very high temperature. This results in a strong air pressure wave, which is responsible for instance, lifting tiles or zinc sheets from roofs. No protection can be provided against such an effect.

The principles already discussed show why a lightning protection system is necessary.

Complete protection is usually impracticable from the standpoint of cost or other reasons. The hazard can greatly be reduced or almost removed by protective means. The protection to be provided must take care of both direct and induced sparks.

3.1 Zones of Protection

Zones of Protection are simply those volumes within which lightning conductors provide protection against a direct lightning stroke by attracting the stroke itself. Zones of protection, for different heights, are shown in the figures below.

As can be seen in (fig. 3.1) structures below 20m are regarded as offering a 45° protection angle (α).

For structures greater than 20 m in height (fig. 3.2) the protection angle of any installed lightning protection conductors up to the height of 20m would be similar to the structures in (fig. 3.1).

For tall structures above 20m in height (fig.3.3), the rolling sphere is recommended to determine the areas where lightning protection may be advisable.

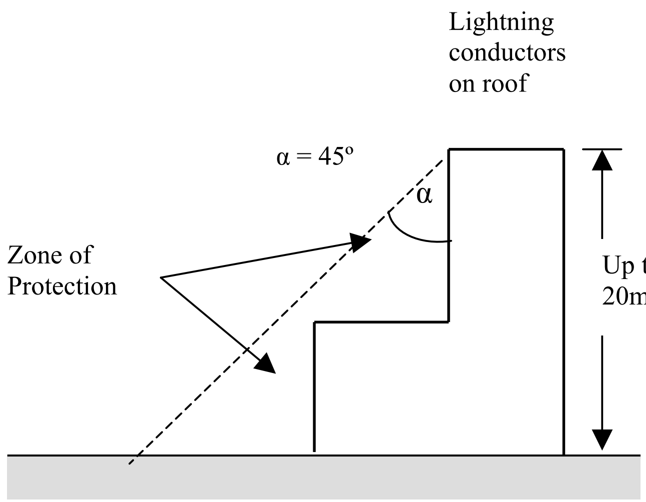


Fig. (3.1)

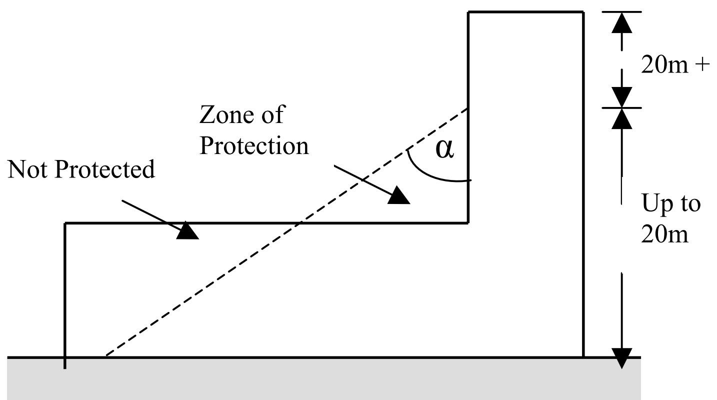


Fig. (3.2)

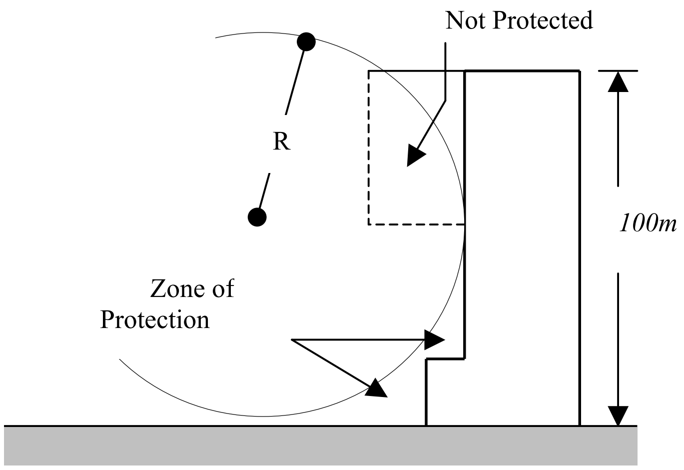


Fig. (3.3)

3.2 Protection System Components

A lightning protection system is a system of rods, cables and grounding designed to intercept a strike and divert it safely to ground, avoiding structural damage to buildings, and other vulnerable objects. It consists of metallic rods, heavy duty cables and a soil ground terminal.
The area over which lightning conductors can attract a lightning flash is variable. This area is also minimally affected by the configuration of the lightning protection conductors, so that vertical and horizontal arrangements are considered to be equivalent. The use of pointed air terminations or vertical finals are, therefore, not regarded as essential, except where dictated by practical considerations.

The main components are:

3.2.1 Air Termination or Air Termination Network

Air termination is that part of lightning protective system, which is intended to intercept lightning discharges (fig.3.4).

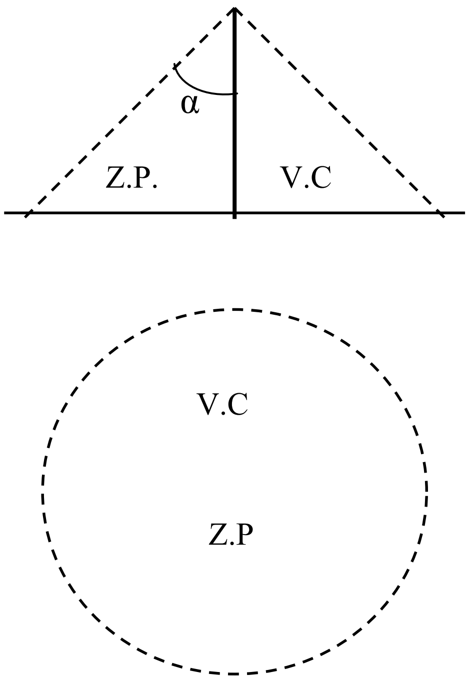


Fig. (3.4.a)
A single vertical air termination

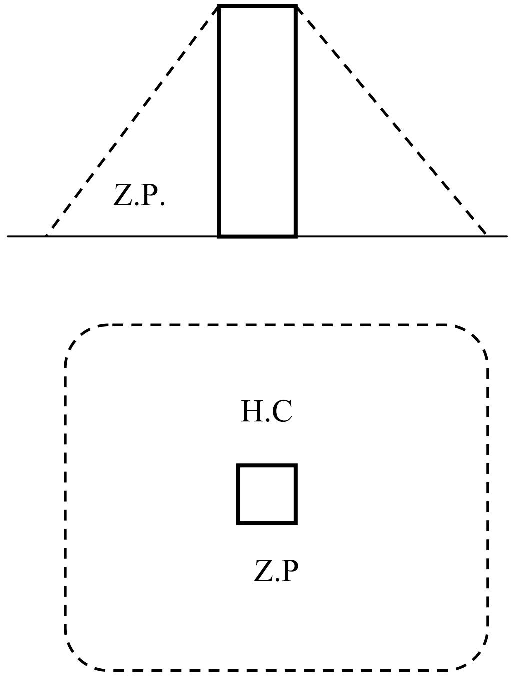
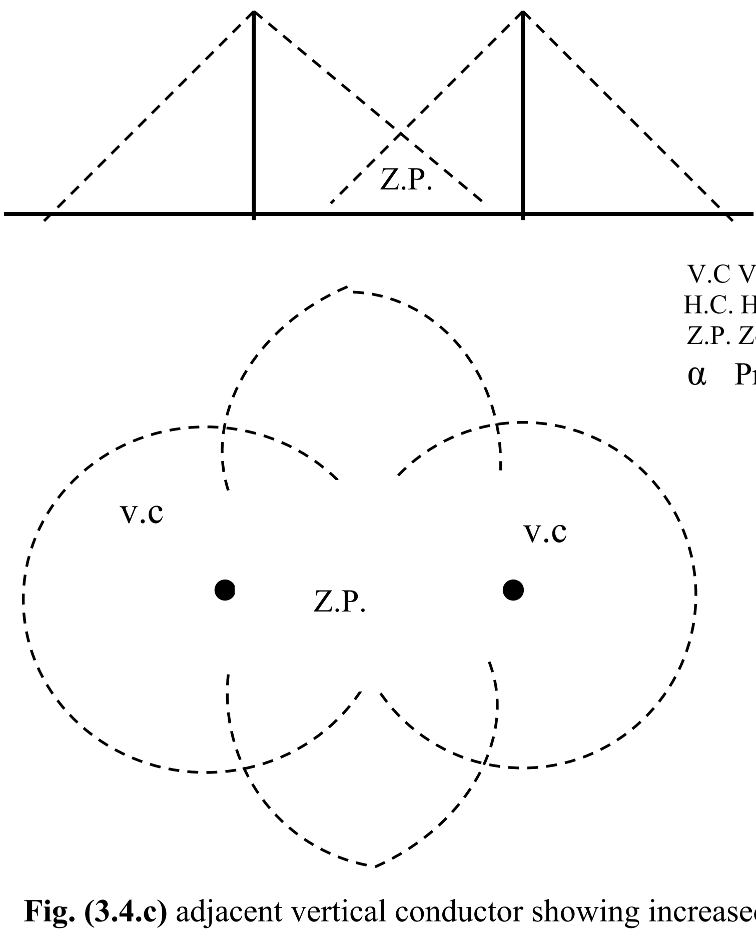


Fig.(3.4.b)
Horizontal air termination



V.C Vertical conductor
H.C. Horizontal conductor
Z.P. Zone of protection
α Protection angle

Fig. (3.4.c) adjacent vertical conductor showing increased zone of protection between conductors

Its main function is to divert to itself a lightning discharge, which may otherwise strike a vulnerable part of the structure to be protected.

The range over which a lightning conductor can attract a lightning stroke, is not constant but it is a function of the severity of the discharges. The range of attraction is thus a statistical quantity.

Thus air termination networks vary from a vertical conductor for a tower to a system of horizontal conductors for flat roofs.

Horizontal air terminations are required for roofs of large horizontal dimensions. No part of the roof should be more than 9 m from a horizontal conductor (fig. 3.5).

All metallic projections should be bonded and form part of the air termination network. If there is a considerable variation in the height of a structure, lower portions should, in addition to their down conductors, be bonded to the down conductors of the taller portions (fig.3.6).

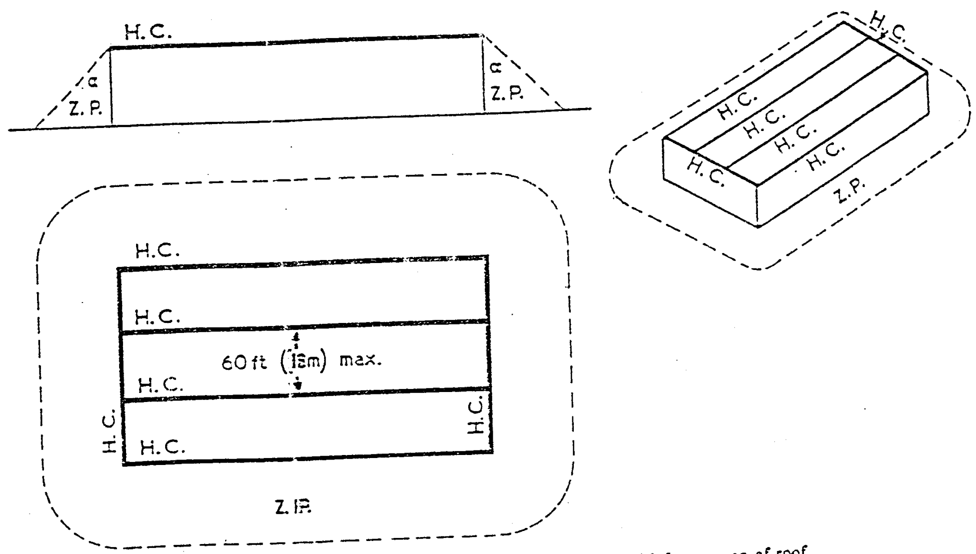


Fig. 3.5.a Horizontal air termination network on a structure with large area of roof

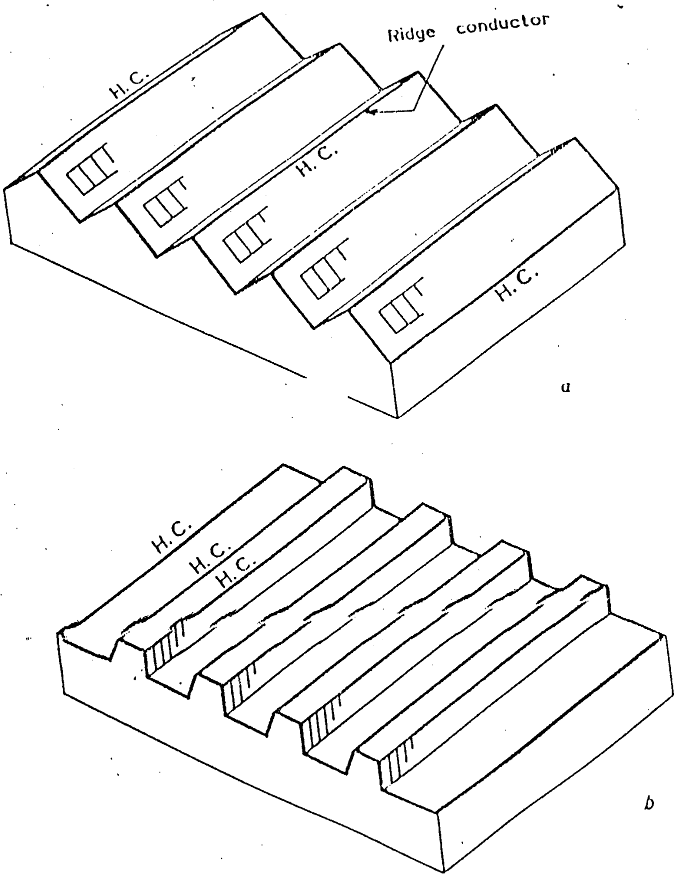


Fig. 3.5.b
Horizontal air termination network on structures with large areas of roof of varying profiles

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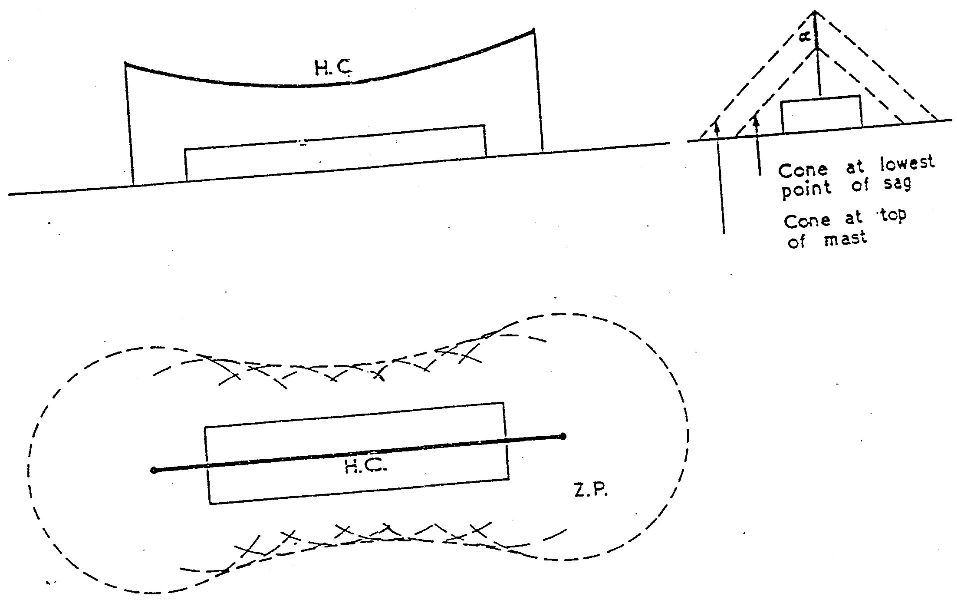

Fig. 3.5.C

Zone of protection of a single catenary

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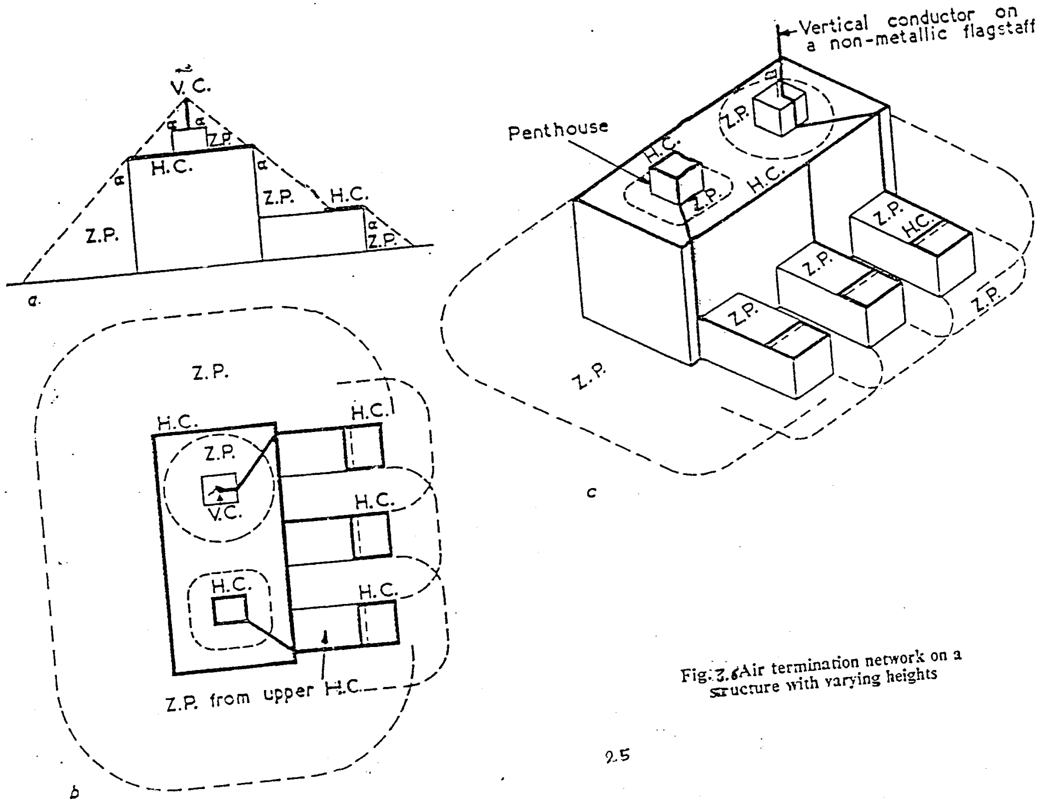


Fig. 3.6 Air termination network on a structure with varying heights

2.5

3.2.2 Down Conductors

A down conductor is defined as a conductor, which connects an air termination with an earth termination. Its function is to provide a low impedance path from the air termination network to the earth termination networks, to allow the lightning current to be safely discharges to earth.

A combination of strip and rod conductors, reinforcing bars, structural steel, etc, can be used as all or part of the down conductor system – providing they are known to offer good electrical conductivity.

The number of down conductor should be decided as follows:

1- A structure having a base area not exceeding 100 m^2 may have only one down conductor.
2- For a structure having a base area exceeding 100 m^2, the number of down conductors should equal the smaller of the following:
   a) One, plus one for every 300 m^2 or part thereof in excess of the first 100 m^2 or.
   b) One for every 30 m of perimeter.
3- For structures exceeding 30 m in height, additional consideration should be applied.

Down conductors should be distributed round the outside walls of the structure. Thus outer walls of buildings may be used for fixing down conductors, but lift shafts should not be used for this purpose.

Where the provision of suitable external routes for down conductors is impracticable or inadvisable, e.g. building of cantilever construction from the first floor upwards, (fig. 3.7), down conductors may be housed in an air space provided by a non-metallic, non-combustible internal duct. Any covered recess not smaller than 76x13-mm full height of the building may be used for this purpose provided it does not contain an unarmoured or non-metal-sheathed service cable.

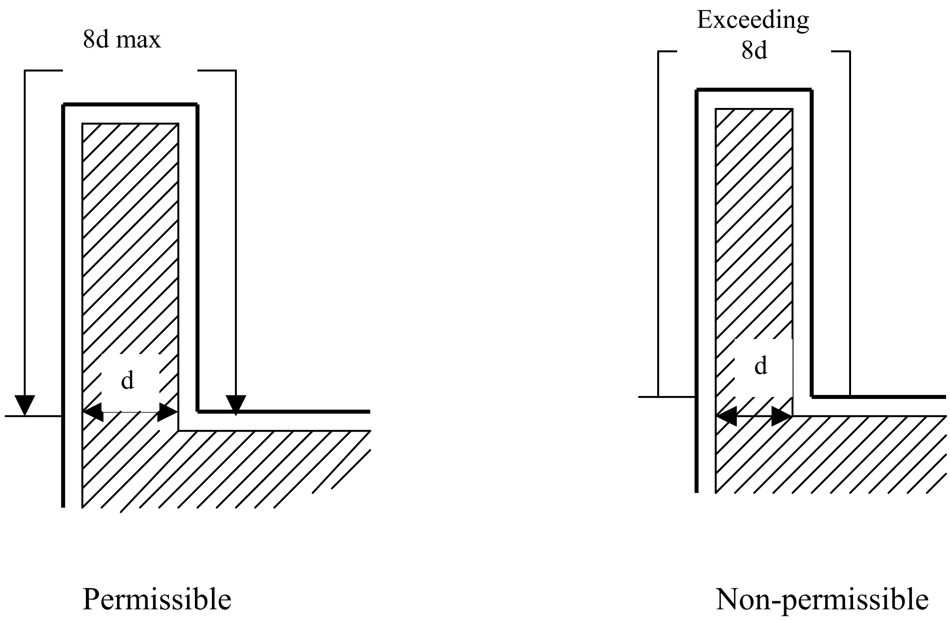
In deciding on the routing of the down conductors, its accessibility for inspection, testing and maintenance should be taken into account.

3.2.3 Joints and Bonds

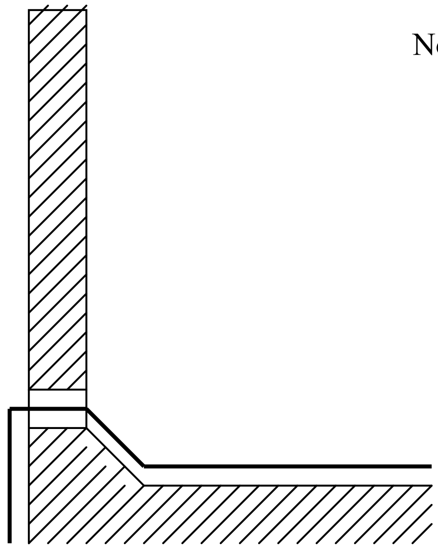
A bond is a conductor intended to provide electrical connection between a lightning protective system and other metal works, and between various portions of the latter.

A joint is a mechanical and electrical junction between two or more portions of a lightning protective system.

The cross sectional area of the bond of external metal forming part of the structure, should not be less than that employed for the main lightning protective system. Internal metal will carry only portion of the lightning current; therefore bonds of smaller cross-section may be used.



(a) General principles of a re-entrant loop in a conductor taken over a parapet wall



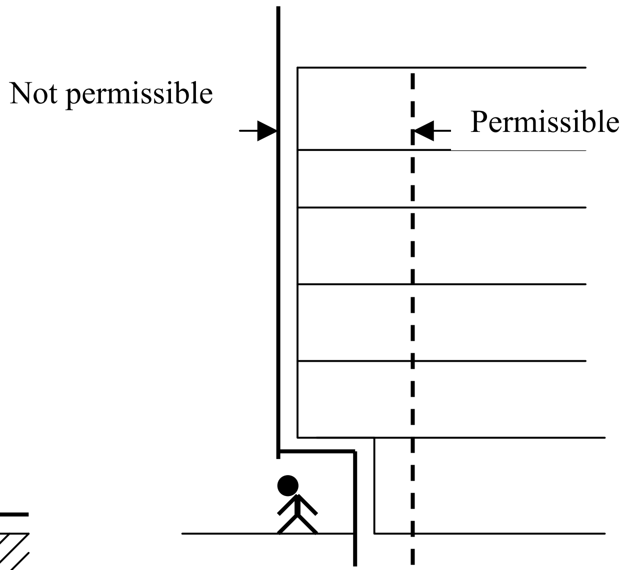


Fig. (3.7)

(b) Permissible method of taking conductor through a parapet wall

(c) Routes for down conductors in a building with cantilevered upper floor

Joints should be as few as possible and joints, bonds should be mechanically and electrically effective, e.g. clamped, screwed, bolted, crimped, riveted or welded.

The resistance from any part of the lightning protective system to earth should not exceed 10 ohms.
Fig. (3.8) shows some of the bonding materials and their typical use.

Ground Clamp

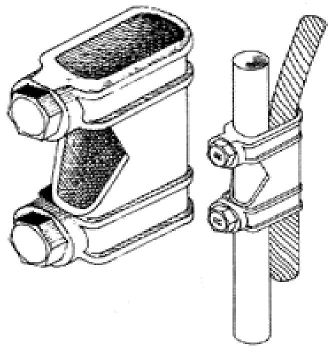


Fig. (3.8.a) Tap Type Ground Clamp

Bimetallic Connector
Cast combination bronze and aluminum connector for making transition from copper cable to aluminum cable. Molded and cast together to exclude moisture from joint.

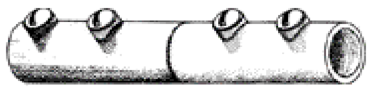


Fig. (3.8.b) Bimetallic Connector

Pipe Bonding Clamp

Heavy cast bronze pipe bonding clamp with 1/4" bolt tension - 1 1/2" cable contact along axis of pipe - for use on all metal pipes - available in three sizes for range of pipes from 3/4" through 4". Capacity for all wires and cables.

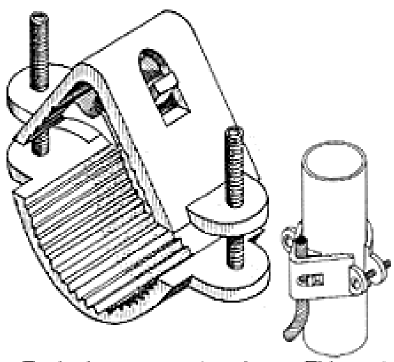


Fig. (3.8.c)

Sill Cock Water Service Clamps
Cast bronze sill cock grounding clamp fits most standard flanges - adjusts with two 1/4" screws - cable lug of stamped copper, lead coated, for use with copper or aluminum cables - 2 1/2" cable contact - tabs must be hammered over flange for positive contact.

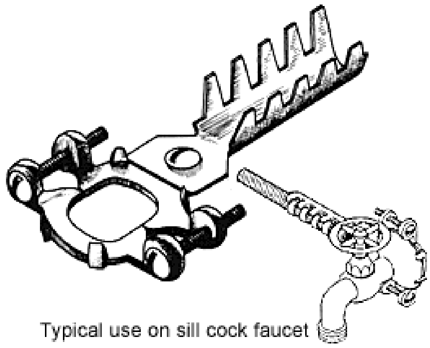


Fig. (3.8.d)

Thru-Wall or Thru-Roof Cable Connector
Combination connector used for thru-wall or thru-roof penetration giving rigid attachment on both surfaces - assemblies may be used in masonry construction with one end concealed - both ends supplied with dead end lug, nuts and washers (stainless steel).

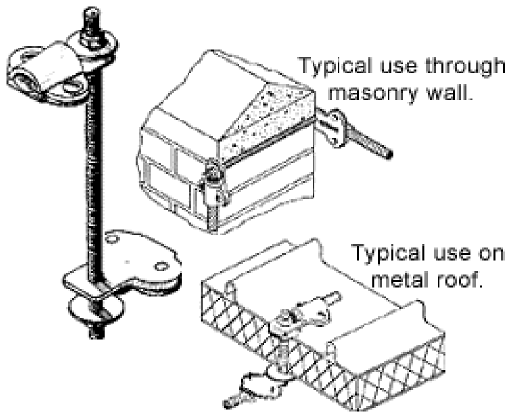


Fig. (3.8.e)

3.2.4 Testing joint
A joint is designed and situated so as to enable resistance or continuity measurement to be made. For a proper protection system each down conductor should be provided with a test joint in such a position that, while not inviting unauthorized interference, it is convenient for use when testing.
This is achieved with a test clamp, fig. (3.9).

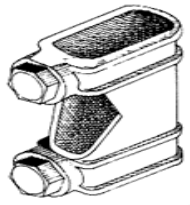


Fig. (3.9) Test clamp

3.2.5 **Earth Termination or Earth Termination Network**

Is that part of the lightning protective system that is intended to discharge lightning currents into the general mass of earth. All parts below the lowest testing points in a down conductor are included in this term.

Earth termination should be connected to each down conductor. Each of these earth terminations should have a resistance to earth not exceeding 10x no. of earth terminations to be provided. The whole of the lightning protection system should have a combined resistance to earth not exceeding 10 ohms.

If the resistance obtained exceeds 10 ohms, this is reduced by adding more earth electrodes, or by salting the soil.

When conditions permit, a common earth electrode is recommended for the lightning protective system and for all other services.

Earth termination should be capable of installation for testing purpose.

3.2.6 **Earth Electrode**

That part of earth termination that makes direct electrical contact with the earth. It consists of metal rods or strips, or a combination of both.

When rods are used, they should be driven into the ground beneath or as close as practicable, to the structure (fig. 3.10). Long lengths in sections coupled by screwed connectors can be built up where necessary to penetrate the substructure of low resistance.

Where ground conditions are more favorable for the use of short rods in parallel, the distance between the rods should be at least equal to their driven length. In order to economize in the use of materials, earth resistance reading should be accessible above ground or, if blow ground, within an inspection box. This connection may then comprise the testing joint.

When strips are used, they should be buried beneath the structure or in trenches at a suitable depth to avoid damage by building operations. Strips should preferably radiate in two or more directions from the point of connection to a down conductor. In the case of strips in parallel or in grid formation, the separation between parallels should not be less than 2.4 m (fig.3.10)

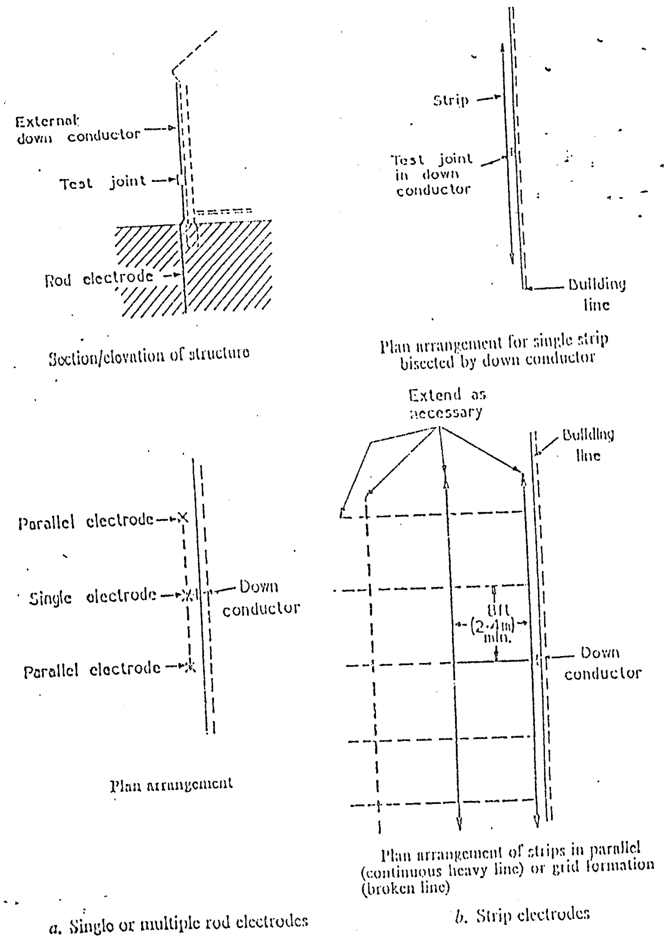


Fig.3.10 Arrangement of earth electrodes

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3.3 Materials used and Specifications

Of vital importance, when designing or installing a reliable lightning protection system is the correct choice of materials and the installation method adopted to ensure satisfactory life span of at least 30 years.

To ensure an effective system and a satisfactory long-term performance all fittings need to be mechanically robust and provide good corrosion resistance qualities in widely differing environments.

In addition the system should provide a low electrical resistance path to earth and have the ability to carry high current repeatedly over the lifetime of installation.

Choosing fittings manufactured from materials outside the range of recommended materials could render the lightning protection scheme vulnerable to corrosion, making it incapable of withstanding the mechanical and electrical forces of a lightning strike.

Tables in (Appendix A) recommend some of the materials to be used for the manufacture of lightning protection components and also, recommend the minimum dimensions of component parts. *Both tables are taken from BS 6651 (1992).*

The integrity of components not designed in accordance with these specifications can not be guaranteed and should not be considered for use in lightning protection systems.

3.4 Construction Sites

When a structure is being erected, all large and prominent masses of steelwork should be effectively connected to earth. This applies to all metal items including steel framework, scaffolding and on-site cranes.

Similarly, once work has commenced on the installation of a lightning protection system, an earth network should be connected at all times.

This also applies to the installation of overhead power lines and railway electrification.

It is very important to install and maintain at the early stages of construction, and adequate earthing system.

Chapter 4

4 Design of A Lightning Protection System

The main purpose of a lightning protection scheme is to shield the building, its occupants and equipment from the adverse effects associated with a lightning strike. These effects could otherwise result in fire, structural damage and electrical interference–leading to equipment damage or electric shock. To perform correctly, the protection scheme must capture the lightning, lead it downwards and then disperse the energy within the ground. The components used to facilitate this are air terminations, down leads, bonding leads and the earth termination (or electrode).

These are all discussed in more details in this chapter, while designing a lightning protection system for a tall building, taking as an example Sudan Telecommunication Head Quarter building (Sudatel HQ).

4.1 Design Considerations

If it has been established that the building requires a lightning protection, certain general design considerations need to be made.

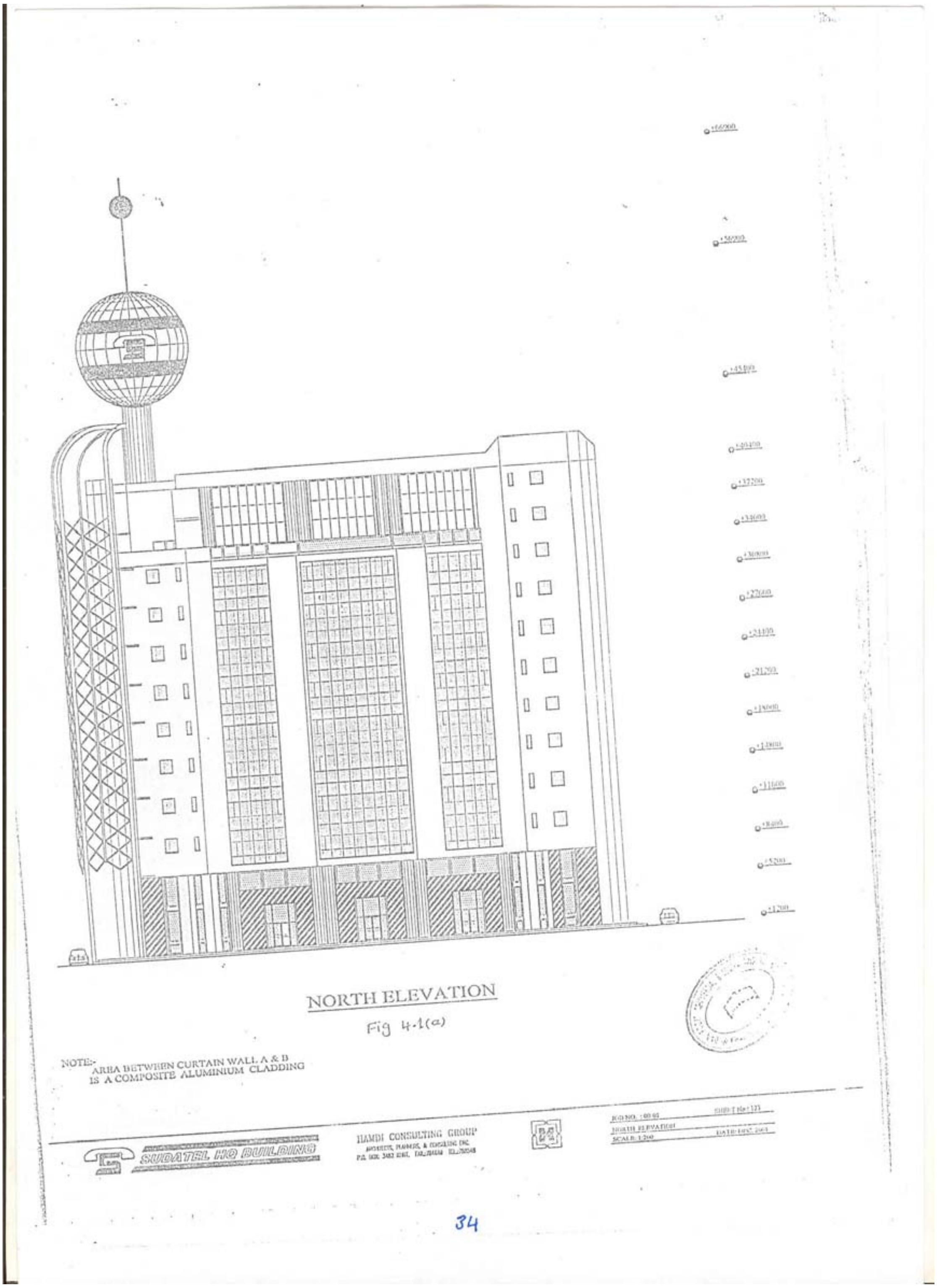
Could, for instance, any of the metallic components in or on the structure be incorporated into the lightning protection scheme? Could the metal in and on the roof be used? Should window rails, window frames and handrails surrounding the structure be incorporated in the protection network? Reinforcing bars or steel frames of the structure may well provide a conductive path within the lightning protection system. With the use of natural conductors in mind, a range of clamps specially suited for these applications should be designed.

If the metallic components in the building are not used, then the structure will require externally fitted conductors. A lightning protection system can incorporate all natural conductors, all externally fitted conductors, or a combination of both.

4.2 Required Information

Generally, in order to design a lightning protection system for such a building, the following information is required:

1- Drawing of the structure requiring protection, showing the roof plan and at least two elevations. These drawings should be clear, precise and have the scale shown. Fig. (4.1).


NORTH ELEVATION
Fig 4-1(a)
NOTE:-
AREA BETWEEN CURTAIN WALL A & B
IS A COMPOSITE ALUMINIUM CLADDING
SUDATEL HQ BUILDING
HAMDI CONSULTING GROUP
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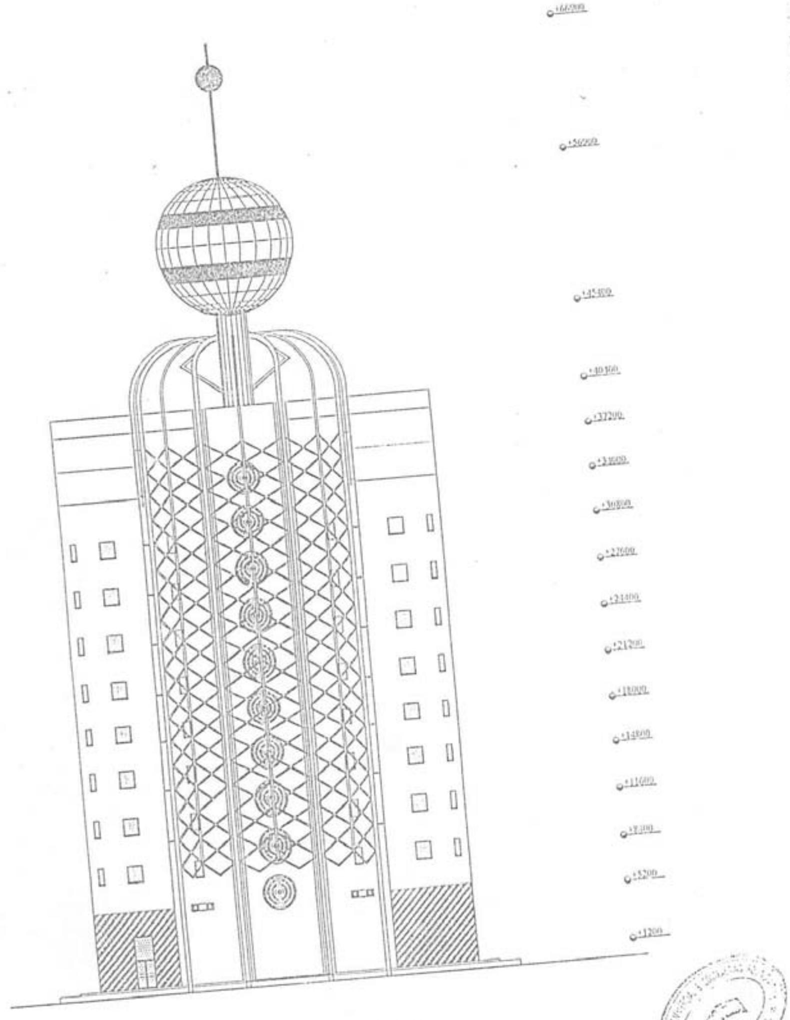

EAST ELEVATION

Fig 4-1 (b)

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2- The materials used in the construction of the structure should be stated along with information on the type of fixing permissible (e.g. can the roof be drilled to take screw plugs).
3- For what purpose is the structure being used? (i.e. it's used will determine the risk category of the structure).
4- The proximity of other structures, trees and its general locality.
5- Information regarding any unusual features such as aerials or mats on the roof of the building which may not be shown on the drawings.
6- At what stage of construction is the structure (i.e. complete, partly-built, etc).
7- Notification of the code to which the scheme is to be designed e.g. BS, VDE, etc.
8- Whether there is any soil resistivity data available?

4.3 The need for Protection

Structures with inherent explosive risks, e.g. explosive factories, stores and damps, fuel tanks, usually need the highest possible degree of protection against the effects of lightning strokes. With many other structures, there will be little doubt as to the need of protection e.g.

1. Those in or near which large number of people congregate.
2. Those concerned with the maintenance of essential public services.
3. Those in areas where lightning strokes are prevalent.
4. Very tall or isolated structures.
5. Structures of historic or cultural importance.

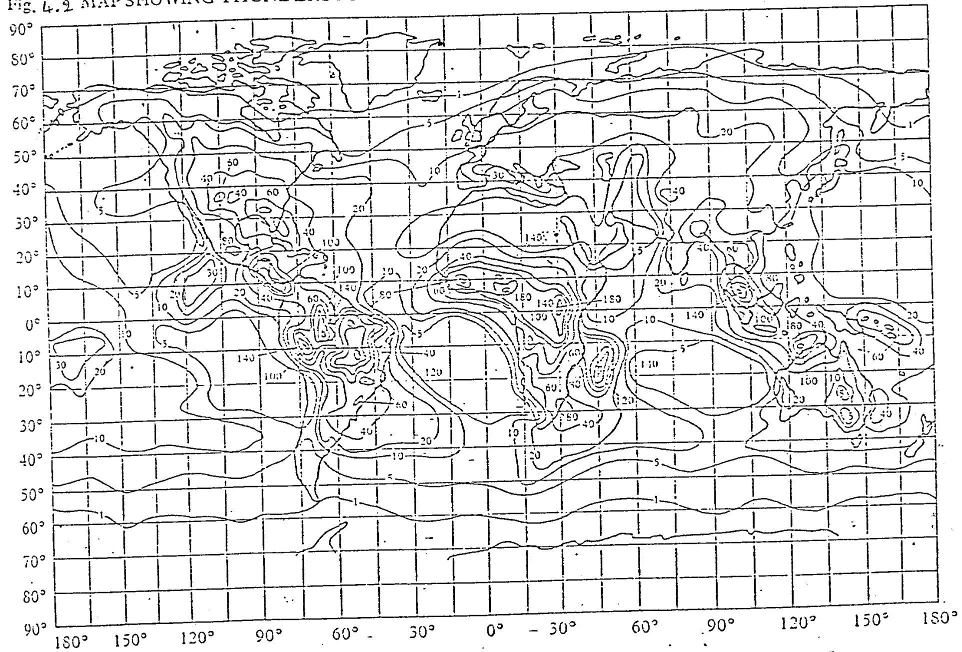
For our building, to decide whether to protect against lightning or not, the following factors have to be considered.

A) The geographical location of the structure
This pinpoints the average lightning flash density or the number of flashes to ground per km² per year.
Fig. (4.2.), is a map, showing thunderstorm days per year through the world (*taken from BS 6651*).

B) The intended use of the structure
That is to say is it a factory or an office block, a school or a hospital?

C) The type of construction
Is it built of brick or concrete? Does it have a steel frame or a reinforced concrete frame? Does it have a metal roof?

Fig. 4.2 MAP SHOWING THUNDERSTORM DAYS PER YEAR THROUGHOUT THE WORLD



NOTE. This map is based on information from the World Meteorological Organisation records for 1955.

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D) What is housed within the structure?
Does it contain valuable paintings, or a telephone exchange with important equipment, or is it used as an old peoples' home?

E) The location of the structure
Is it located in a large town or forest or on an isolated hillside?

F) The topography of the country
Is the structure located in a flat countryside or in a mountainous area?

G) The height of the structure (effective collection area)
The effective collection area of the structure is the plan area projected in all directions taking into account the structure height. The significance being, the larger the structure, the more likely it is to be struck.

H) Lightning prevalence
Is the number of storm days per year.

Based on the table below giving a degree of importance for each of these factors, an index factor is obtained, which can then be used as a guide to whether or not protection of the H.Q. is advisable.

Table 1

Index figure B (use of structure)

Use to which structure is put	**Value of index B**
House and other buildings of comparable size.	2
House and other buildings of comparable size with outside aerial.	4
Factories, workshops and laboratories	6
Office blocks, hotels, blocks of flats and other residential buildings other than those included below	7
Places of assembly, e.g. churches, halls, theaters, museums, exhibitions, department stores, post offices, stations, airports and stadium structures.	8
Schools, hospitals, children's and other Homes.	10

The building is an office block; hence, the value of this index is equal to 7.

Table 2

Index figure C (type of construction)	
Type of construction	**Value of index C**
Steel frame encased with any roof other than metal.	1
Reinforced concrete with any roof other than metal.	2
Steel frame encased or reinforced concrete with metal roof.	4
Brick, plain concrete or masonry with any roof other than metal thatch.	5
Timber framed or clad with any roof other than metal or thatch.	7
Brick, plain concrete, masonry, timber framed but with metal roofing.	8
Any building with a thatched roof.	10

The building is a reinforced concrete frame, without metal roof. 2 gives the value of this index.

Table 3

Index figure D (contents or consequential effects)	
Contents or consequential effects	**Value of index D**
Ordinary domestic or office buildings, factories and workshops Not containing valuable or specially susceptible contents.	2
Industrial and agricultural buildings with specially susceptible contents.	5
Power stations, gas installations, telephone exchanges, radio stations.	6
Key industrial plants, ancient monuments and historical buildings, museums, art galleries or other buildings with specially valuable Contents.	8
Schools, hospitals, children's and other Homes, place of assembly.	10

Our building contains special valuable and important equipment, such as computers and data center. The value of this index is equal to 8.

Table 4

Index figure E (degree of isolation)	
Degree of isolation	**Value of index E**
Structure located in large area of structure or trees of the same	

or grater height, e.g. in a large town or forest.	2
Structure located in an area with few other structures or trees with similar height.	5
Structure completely isolated or exceeding at least twice the Height of surrounding structure of trees.	10

It is located in a large area of structures in a large town; hence 2 gives the value of index figure for the degree of isolation

Table 5

Index figure F (type of country)

Type of country	Value of index F
Flat country of any level.	2
Hill country.	6
Mountain country between 300m and 900m.	8
Mountain country above 900m.	10

The structure is located in a generally flat country; the value of this index figure is given as 2.

Table 6

Index figure G (height of structure)

Height of structure above ground		Value of index G
Exceeding	**Not exceeding**	
	9 m	2
9 m	15m	4
15m	18m	5
18m	24m	8
24m	30m	11
30m	38m	16
38m	46m	22
46m	53m	30

From fig. (4.1), showing the east and north elevations, the height of the structure is 66.9 m including the sphere decoration, and 40.4 m without the sphere. Taking the main building height as (40.4m), the value of the index figure corresponding to the height of the structure is 22.

Table 7

Index figure H (lightning prevalence)

Number of storm days per year		**Value of index H**
Exceeding	**Not exceeding**	
	3	2
3	6	5
6	9	8
9	12	11
12	15	14
15	18	17
18	21	20
21		21

The frequency of lightning applicable to this area, (i.e. the number of storm days per year), from the map of fig. (4.2) is exceeding 10, then from table (7), the index value is 11.

Based on the values of the indices, arrived at by reference to the tables 1 to 7 and the map of thunderstorm days, these values are added together to give the resultant figure of 54.

Since figure 40 is used as the criterion, the resultant figure of 54 indicates that the need of protection for Sudatel H.Q. is essential.

Another method is the calculation of the overall risk factor, where, the 10^{-5} (1 in 100,000) is the criteria for determining whether protection is necessary or not, see (Appendix B).

4.4 The Major Components

The principal components of the lightning protection system for such a building should comprise the following:

4.4.1 Air Termination Networks

As stated earlier it is now accepted that lightning can strike the upper part of the structure. Standards now introduce the concept of air termination networks on all sides of tall buildings (i.e. vertical air termination networks). No part of the roof within the air termination networks should be more than 5 m from a conductor. Since the building has a large flat roof, this will be achieved typically by a network mesh of 10 m X 20 m.

To minimize the likelihood of a lightning stroke damaging the side of the building, it is suggested that the rolling sphere method be applied to identify those areas where an extension of the air termination network should be considered. This method involves rolling an imaginary sphere of 60m radius over the structure. The areas touched by the sphere are deemed to require protection. On a tall structure, this can obviously include the sides of the building.

4.4.2 Down Conductors

Down conductor siting and distancing is often dictated by architectural circumstances. There should be one down conductor for every 20m or part thereof of the building perimeter at roof or ground level. These should be evenly spaced and distances apart of more than 20m are avoided if possible.

Since the building is 40m height the distance between down conductors should be reduced to 10m.

Down conductors should be routed as directly as possible from the air termination network to the earth termination network to avoid the risk of side flashing.

Re-entering loops are also to be avoided. Standards recommend that the length of the conductor forming the loop should not exceed eight times the width of its open side.

It is allowed to use ‘ natural conductors’ such as bars and structural steelwork, provided that they are electrically continuos and adequately earthed.

4.4.3 Earth Termination Networks

Each down conductor must have a separate earth termination. Moreover provision should be made in each down conductor, for disconnection from the earth for testing purposes. The resistance to earth of the complete lightning protection system measured at any point should not exceed 10 ohms. With the test clamp disconnected, the resistance of each individual earth should be no more than ten times the number of down conductors in the complete system.

For example a system with 15 down conductors, the individual earth readings should be no more than 10 x 15 = 150 ohms.

Several types of earth electrodes are permissible, but by far the most commonly used are deep driven earth rods, fig. (4.3).

The combined earth rod length of the system should be no less than 9m, whilst each individual earth rod should be no less than 1.5m in length.

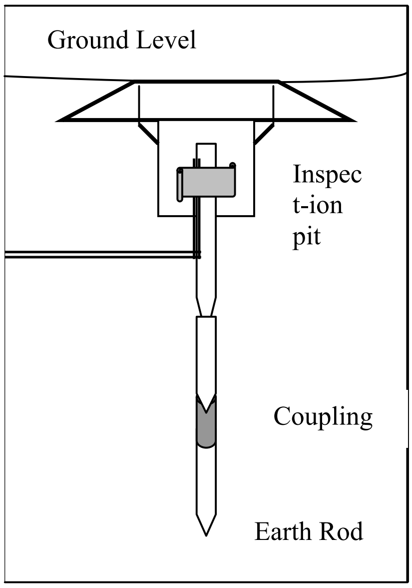

Fig. (4.3) Deep Driven Earth Electrode

If ground conditions make deep driving of earth rods impossible, a matrix arrangement of rods coupled to one another by conductors can be used. If possible, the earth rods must be spaced at distances at least equal to their driven depth, fig. (4.4).

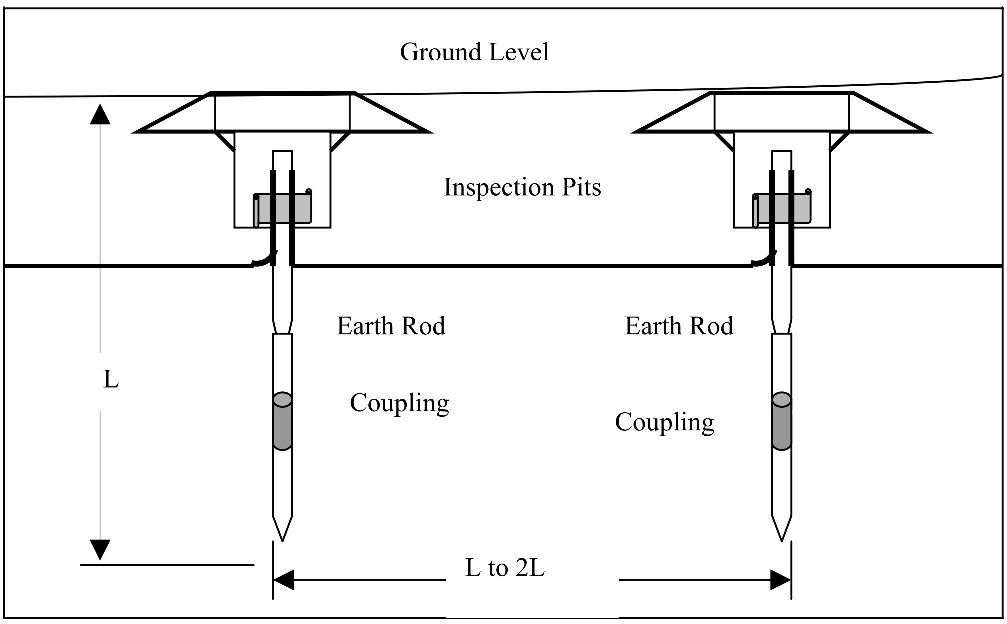

Fig. (4.4) Spacing of Parallel Earth Rod Electrodes

If earth rod cannot be driven in a parallel line a ‘Crows Foot’ configuration can be used, ensuring that the spacing / depth ratio is still maintained.

High resistivity soil conditions can be overcome by backfilling earth rods with a suitable medium such as Marconite conductive concrete which effectively increases the diameter of the earth rod and hence its surface area, thus lowering its resistance to earth.

Marconite conductive concrete is a non-corrosive permanent solution to earthing problems providing a fixed earth reading that will not vary significantly regardless of seasonal factors and without maintenance.

4.4.4 Bonding

All metal work, including water pipes, handrails, air conditioning units, window frames, cladding, metal roofs, etc, in the vicinity of the lightning protection system must be bonded to the main electrical earth, as well as any earthing system present in the structure.

It is vital that all exposed metalwork is bonded into the lightning protection installation to prevent side flashing, fig. (4.5).

4.4.5 Corrosion

The correct choice of materials for a lightning protection system design is important. Metals fitted must be compatible with the metal or metals used externally on the structure over which the system passes or with which it may be in contact.

Aluminium and copper, the two metals most commonly used in lightning protection systems, are not compatible, so great care must be taken when both are used in a system- particularly where they come into contact with each other.

If Aluminium is selected as the material for air termination networks and down conductors, it has to be connected to copper at the test clamp. This connection should be positioned at the beginning of the earth termination network. This is because both standards and the earthing codes do not permit Aluminium to be buried underground.

The contact surfaces of dissimilar metals should be kept completely dry and protected against the ingress of moisture, otherwise corrosion will occur.

A particular effective means of excluding moisture is to use inhibitor pastes, bitumastic paint, or approved protective wrappings.

As Aluminium is prone to corrosion when in contact with Portland cement and mortar mixes, Aluminium need to be fixed away from the offending surface with an appropriate fixing.

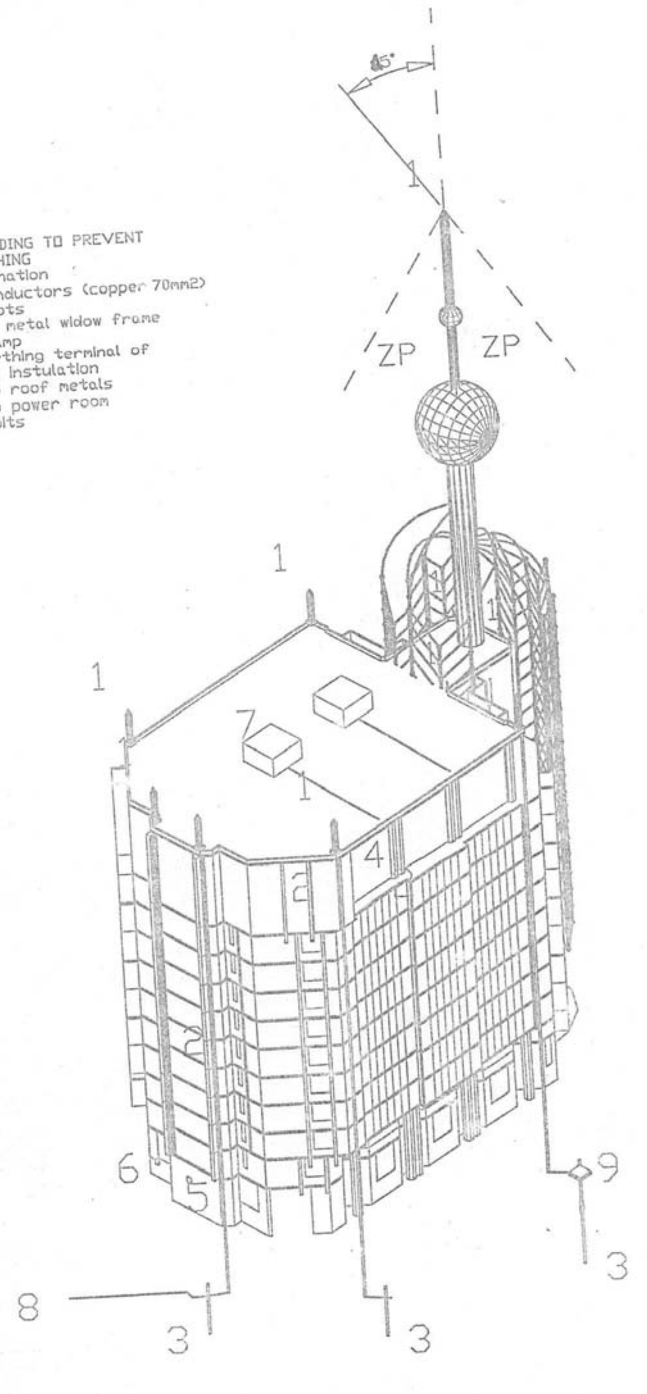

Fig.4.5 BONDING TO PREVENT SIDE FLASHING
1.air termination
2.down conductors (copper 70mm2)
3.earth rots
4.bond to metal widow frame
5.test clamp
6.main earthing terminal of electrical instulation
7.bond to roof metals
8.bond to power room
9.earth pits

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4.5 Inspection, Testing, Records and Maintenance

For a reliable lightning protection system, details of testing, inspection, and recording results should be maintained.

The lightning protection system should be tested every 12 months, or preferably slightly less in order to vary the season in which tests are made.

Of particular importance is the regular detailed examination of the complete lightning protection system for any evidence of corrosion. If this check is not carried out, then vital components within the lightning protection system, which may suffer from corrosion and which could exhibit a high resistance joint, could be missed. This will have a detrimental effect on the whole lightning protection system making it unattractive, with high impedance path for the lightning current to follow.

To minimize this problem, along with regular inspection, the selection of the correct materials that ensure a life span of 30 years should be made in accordance with the recommendations of adopted standard.

Chapter 5

5 Protection of Electrical Equipment against Lightning

A major hazard to electrical systems is the lightning strokes and the switching surges.

Of vital important to protect substations, transmission and distribution systems against the abnormal overvoltages caused by the direct and the remote lightning strokes, namely; protection against the wave front, magnitude of the wave and the frequency of propagation, of both voltages and currents.

5.1 Lightning Overvoltages

Abnormal overvoltages due to several causes may occur in power systems, and they are superimposed on the operating voltages. The overvoltages may be power frequency (50 Hz) or transient overvoltages.

The main causes of transient overvoltages are lightning discharges and switching operations, i.e. the opening and closing of circuit breakers.

Atmospheric discharges that electrical equipment are to be protected from are detailed in this chapter. These include overvoltages from direct lightning strokes and remote lightning strokes (indirect lightning strokes).

5.1.1 Direct Strokes

The statistical average of the magnitude of the current discharge from lightning is 20kA. The current-time relation is of the form:

$$I = I_{peak}\,[\exp(-\alpha t) - \exp(-\beta t)] \qquad (5.1)$$

And the lightning waveform is shown in (fig. 5.1).

When lightning strikes an overhead line directly, half of this current surge propagates in either direction, and if the surge impedance of the line is Zo, each current surge is associated with a voltage surge of the same waveform as that of the current, (fig. 5.2).

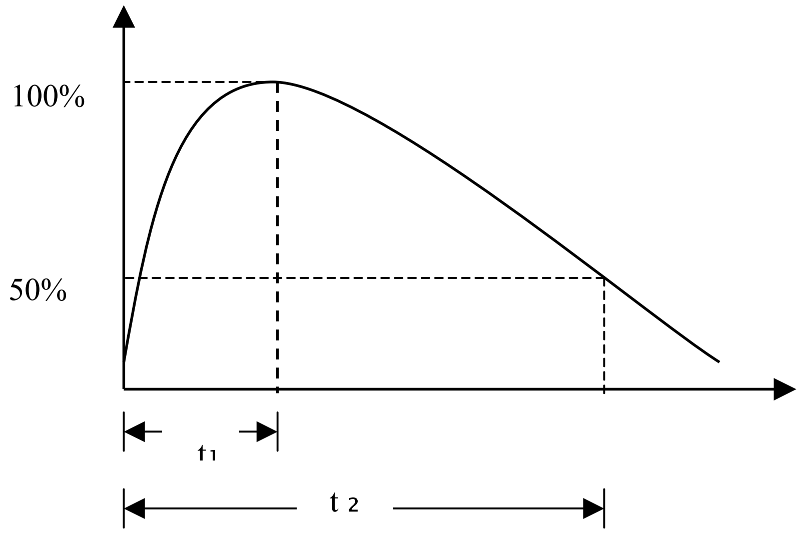
$$V = \tfrac{1}{2}\, Z_o I_p\,[\exp(-\alpha t) - \exp(-\beta t)] \qquad (5.2)$$

For $Z_o = 350\ \Omega$ and $I_p = 20$ kA

$$V = V_p\,[\exp(-\alpha t) - \exp(-\beta t)] \qquad (5.3)$$

Where $V_p = 3500$ kV.

These surge voltages propagate along the overhead lines at the speed of light ($3x10^8$ m/s), and if no precautions are taken, they appear across the electrical equipment connected to the overhead line.



t_1 = waveform front ~ 2 µs
t_2 = wave tail ~ 50 µs

Fig. (5.1) Lightning current waveform

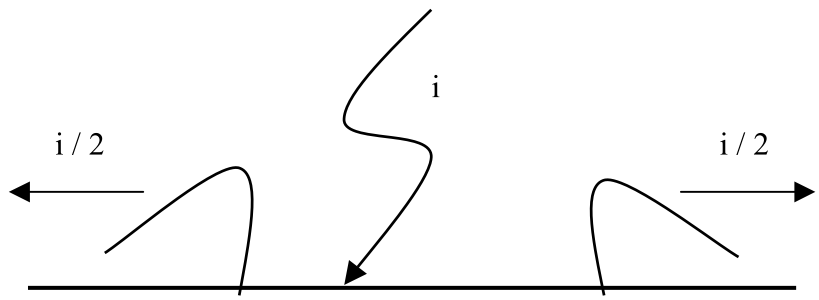


Fig. (5.2) Direct lightning stroke on overhead line

5.1.2 Indirect Lightning Strikes

Remote lightning strokes may induce high voltages into the low-voltage overhead lines feeding the system or building.

5.2 International Specification for Lightning Current

The tables below show typical values of current parameters and protection levels for different strokes. Care must be taken when protection is required against these large magnitudes and wave fronts (*The values are taken from IEC 61312-1 standards*).

5.2.1 Lightning current parameters of the first stroke

Table 11

Current Parameters		**Protection Level**		
		I	**II**	**III- IV**
Peak Current I	(kA)	200	150	100
Front Time T_1	(µs)	10	10	10
Time to half value T_2	(µs)	350	350	350
Charge of the short duration stroke Qs	(C)	100	75	50
Specific energy W/R^2	(MJ/Ω)	10	5.6	2.5

- Since the substantial part of the total charge Qs is contained in the first stroke, the charge of all duration strokes is considered to be incorporated in the given values.
- Since the substantial part of the specific energy W/R is contained in the first stroke, the specific energy of all duration strokes is considered to be incorporated in the given values.

5.2.2 Lightning current parameters of the subsequent stroke

Table 12

Current Parameters		**Protection Level**		
		I	**II**	**III- IV**
Peak Current I	(kA)	50	37.5	25
Front Time T_1	(µs)	0.25	0.25	0.25
Time to half value T_2	(µs)	100	100	100
Average stepness I / T_1	(kA / µs)	200	150	100

5.2.3 Lightning current parameters of the long duration stroke

Table 13

Current Parameters		**Protection Level**		
		I	**II**	**III- IV**
Charge	(C)	200	150	100
Duration T_1	(s)	0.5	0.5	0.5

Average current – Approximately Q / T

5.3 Methods of Protection

According to the tables shown above, many methods are used for the effective protection against lightning, all of these methods used either one of two philosophies:

- Modification of the surge waveform.
- Diversion of the surge from electrical equipment.

5.3.1 Modification of Overvoltage Surges

The severity of an overvoltage surge is determined by its peak value and its initial rate of rise. Obviously, the higher the peak, the more severe is the surge and the steeper the rate of rise, the more dangerous is the surge.

Attempts are made to reduce the peak and to increase the time to peak value (wave front).

a) Peak Reduction

Switching-in of resistance across circuit breaker contacts reduces the high overvoltages produced on operating, especially; capacitive circuits.

b) Surge Modifier

A surge modifier is produced by the connection of a shunt capacitor between line and earth, or inductor in series with the line.

Oscillatory effects are reduced by the inclusion of damping resistor. Surge modifiers are connected in series with the line entering the substation and attempt to reduce the steepness of the waveform, hence its severity.

5.3.2 Surge Diversion

The idea is to prevent the flow of the high surge current through the equipment by providing a low impedance path parallel to the equipment. The basic requirements for a successful surge diverter are, therefore:

- Should pass no current at normal voltage.
- Should operate as quickly as possible after the abnormal overvoltage arrives.
- Should interrupt the power-frequency follow-on current after a flashover.

Surge diversion can be achieved by the following arrangements:

a) Rod Gap

Rod Gap, Horn Gap or Arcing Ring is the simplest and cheapest method for plant and equipment protection against surges.

The gap is connected immediately across the equipment to be protected fig. (5.3 .a).

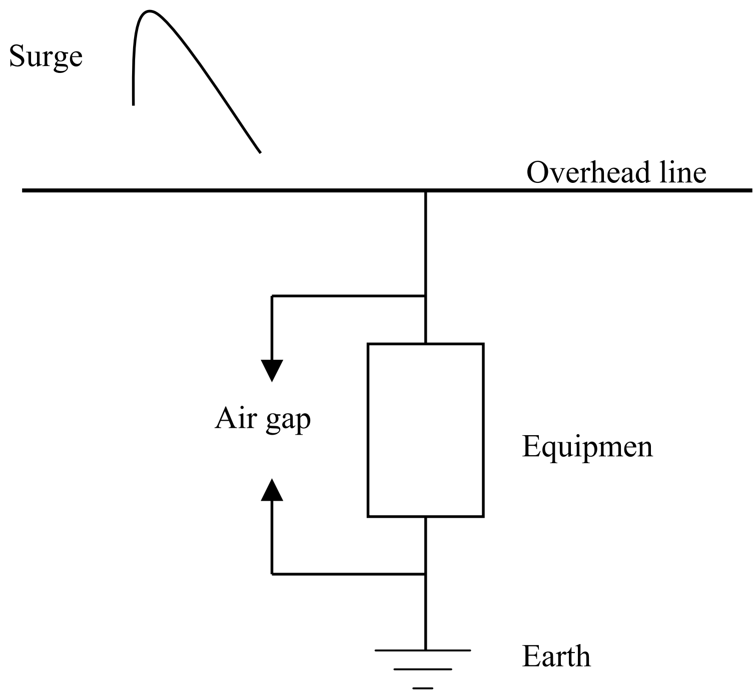


Fig. (5.3.a) Rod Gap arrangement

The gap flashes over under the high-voltage surge, and the surge energy is dissipated to earth.

Exhibits all basic requirements except that, it does not interrupt the follow-on current (the power-frequency current which flows in the path created by the flashover).

The rod gap is set to breakdown at a voltage approximately 30 % below the withstand level of the protected equipment. Rod-Gap breakdown characteristics are shown in fig. 5.3 (b).

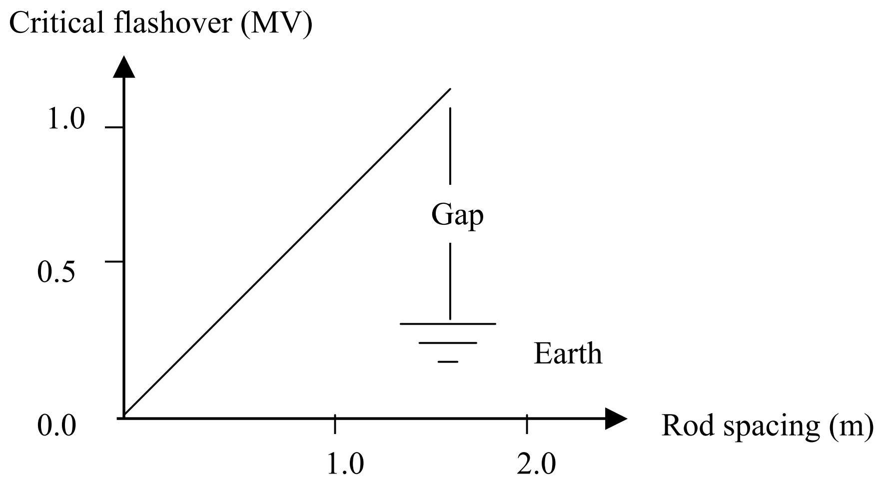


Fig. (5.3.b) Effect of rod spacing on flashover of rod gap – lower rod grounding

b) Expulsion Gaps or Tubes (Protector Tubes)

This is a spark gap in a fiber tube fig. (5.4).

It interrupts the power frequency flow-on current. When sparkover occurs between the electrodes, the flow-on current arc is contained in a relatively small fiber tube.

The high temperature of the arc vaporizes some of the organic material of the tube wall, causing a high gas pressure to build up in the tube. This gas prossesses considerable turbulence and it extinguishes the arc. The hot gas rapidly leaves the tube, which is open at the ends. Very high currents are interrupted in such tubes.

The breakdown voltage is slightly lower than plain rod gaps for the same spacing.

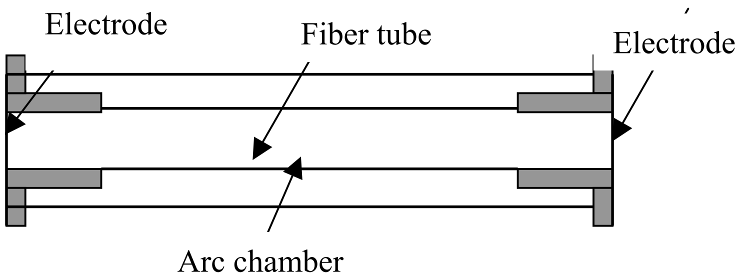


Fig. (5.4) Expulsion tube

c) Lightning Arresters

This is the most effective and most commonly used for surge diversion fig. (5.5).

A porcelain bushing contains a number of spark gaps in series with silicon carbide disc with non-linear resistance characteristics; i.e. possessing low resistance to high currents and high resistance to low currents. It obeys a law of the form:

$$V = a\,I^{0.2} \tag{5.4}$$

a = constant and depends on the material and size of the disc.

The overvoltage breaks down the gap and the power-frequency follow-on current is determined by the disc and is limited to such value that the gaps can quickly interrupt it, at the first current zero. For high voltages, stacks of several units are used.

Multiple spark gap diverters can withstand high rates of rise of recovery voltage, but the non-uniform distribution of voltage across the gaps presents a problem. This is overcome by connecting non-linear resistors in parallel with the gaps to provide the voltage grading required.

d) Earth Wires

An earth wire is run above and parallel to the main conductors of the transmission line and is supported on the same tower and is earthed at every tower footing.

Earth wires shield overhead conductors from direct lightning strokes and lessen the effects of surges from indirect strokes. Effectiveness of shielding is described by an angle $\alpha \sim 35^\circ$.

For reason of economy, earth wires are installed over the last kilometers or so of a transmission line immediately before it enters a substation.

However, earth wires are used throughout the distribution networks especially in countries where thunderstorms are prevalent. The earth wire is shown in fig. (5.6).

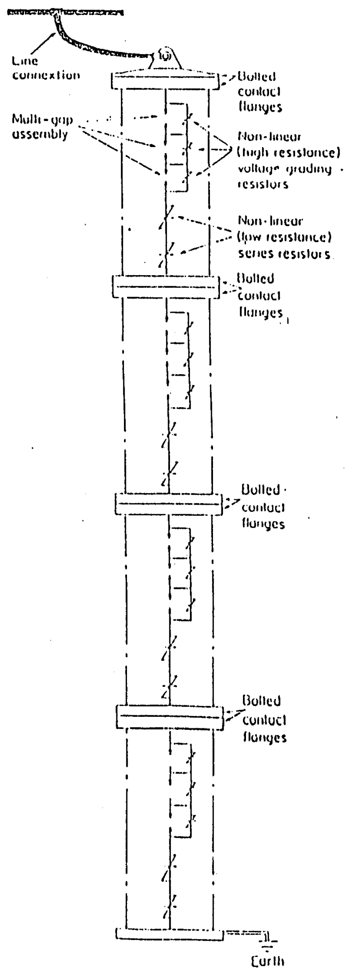


Figure 5.5 Equivalent circuit of components comprising a single-phase four-unit surge diverter stack. (*Permission of the Electricity Council.*)

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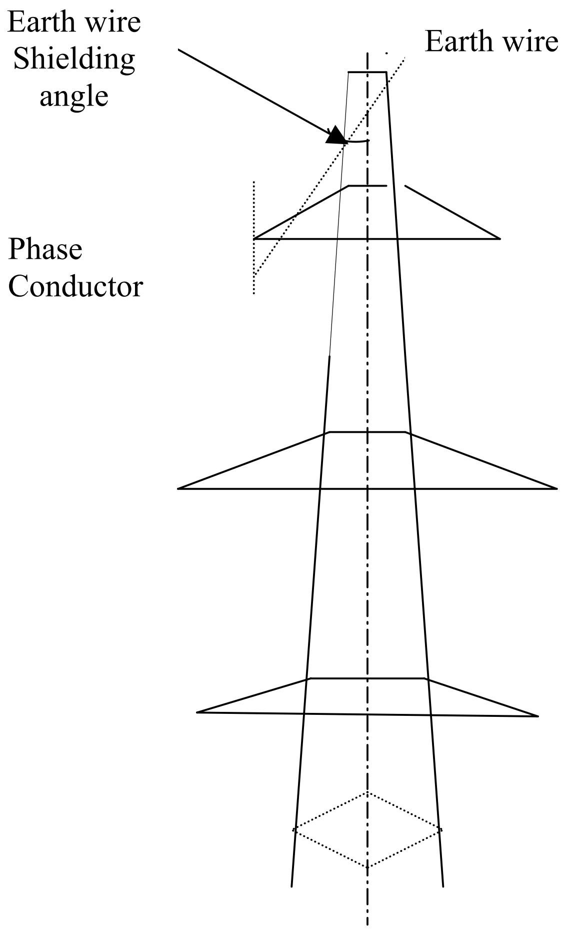

Fig. 5.6 Single earth wire protection; shield angle α normally 35˚

5.4Measures Relating to Internal Lightning Protection

The function of internal lightning protection is:
- To protect personnel inside the building from the effects of lightning strike.
- To protect the installed electrical equipment from destruction by branch lightning currents entering in an uncontrolled manner.

5.4.1 Lightning protection by equipotential bonding

A lightning protection system cannot prevent lightning discharges from happening, but it must be capable of effectively protecting persons or property.

To prevent the danger of uncontrolled flashover, all metallic parts, electrical equipment, the lightning protection system and the earthing system are interconnected through conductors and cables to affect equipotential bonding, fig. (5.7).

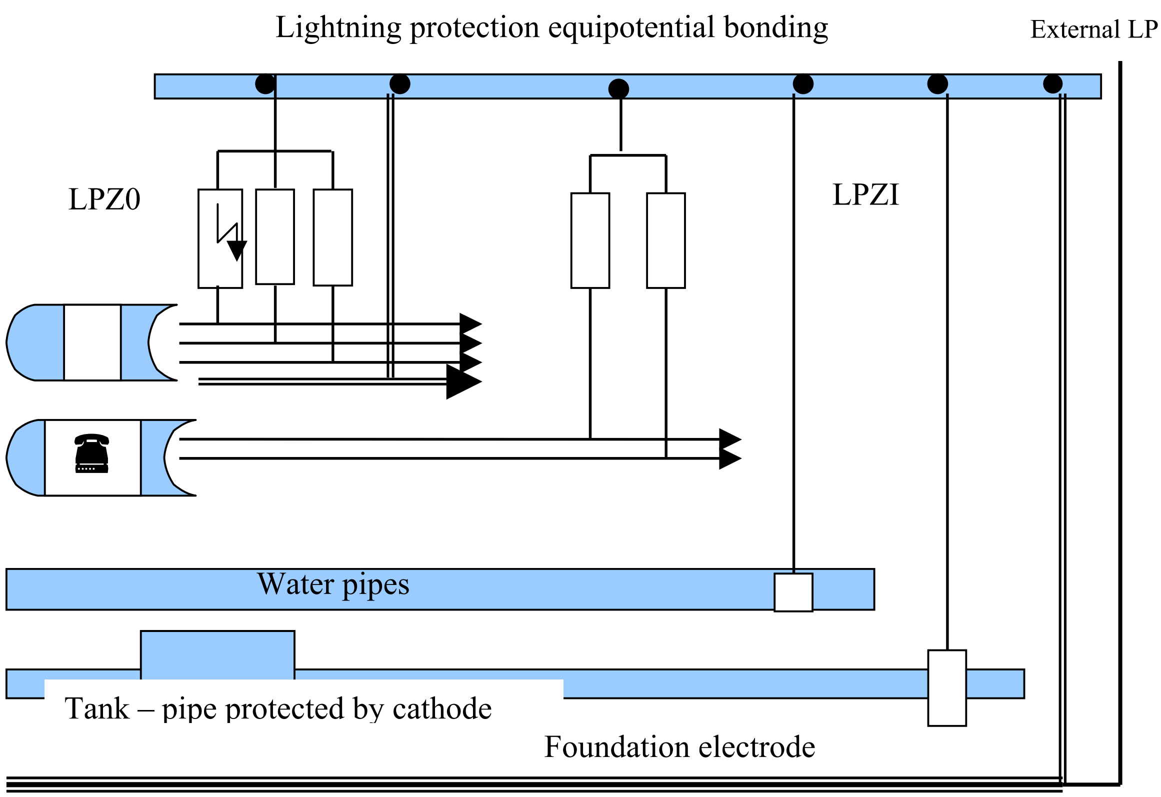

Fig. (5.7) lightning protection equipotential bonding for public services entering the building

Standards require that equipotential bonding should be provided at the following places:

- In the basement or approximately at ground level. Equipotential bonding conductors must be connected to the equipotential bonding bar that is connected to the earthing system. In large buildings, several equipotential bonding bars may be installed, provided that they are interconnected.

- Above ground, in buildings more than 20 m in height, in vertical intervals of not more than 20 m.

- Where exposure requirements of down conductors in the external lightning protection system for buildings are not complied with.

If no external lightning protection system exists and protection of incoming lines against the effects of lightning is required, a lightning protection equipotential bonding must be provided.

If lightning strikes the external lightning protection system of a building, the lightning surge current is divided according to the impedance of each system, which is connected to the lightning protection equipotential bonding bar and through which it discharges to ground.

As defined in the international standard (VDE), it can be assumed that lightning branch currents are evenly distributed among the public services entering the building. Fig. (5.8).

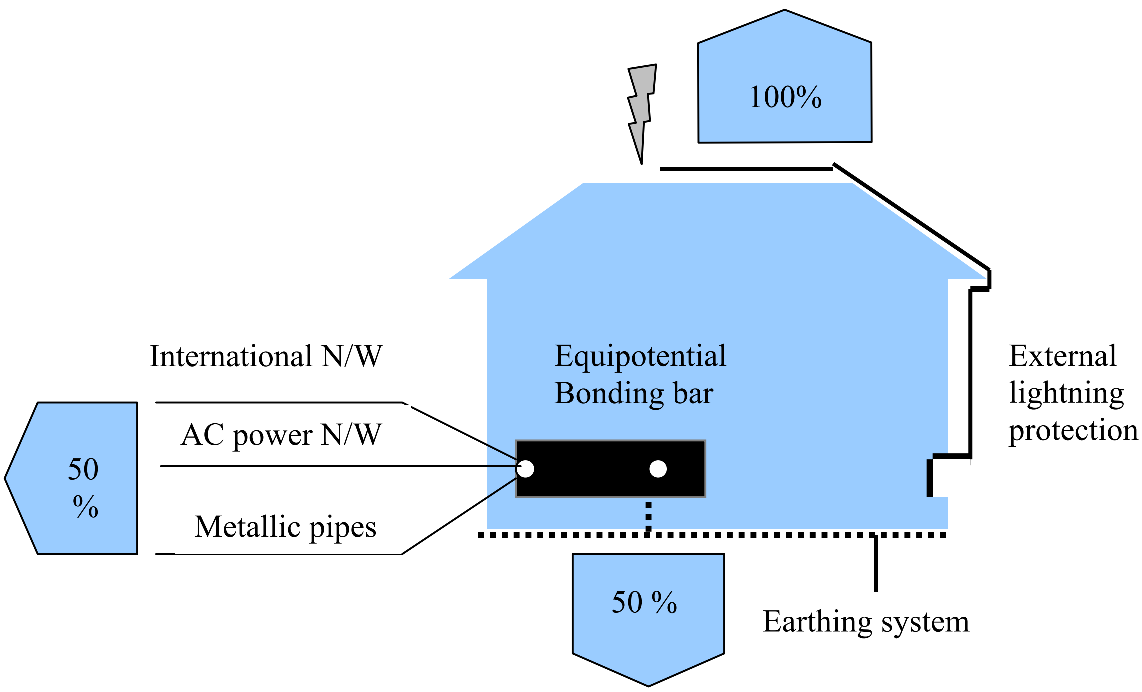

Fig. (5.8) Assumed distribution of lightning surge current

5.4.2 Lightning protective devices used in power supply systems

To prevent uncontrolled dielectric breakdown and flashover and hence the uncontrolled flow of lightning branch currents, after a direct lightning stroke which raises the potential inside the building, all AC power supply system conductors must be fitted with suitable protective devices.

As defined by standards, the use of arresters capable of carrying lightning currents at the input point of the electrical system is mandatory. It is absolutely necessary to coordinate lightning current arresters and downstream overvoltage arresters, taking the waveform of the high-energy lightning surge current (10 / 350 μs) into account.

The requirements imposed on the arresters differ, depending on the class of protection. Distinction is made as to whether they are intended to carry lightning currents, or part of it or merely to limit overvoltages at relatively low surge current levels.

Arresters are grouped and their test parameters determined in compliance with classes B, C and D.

Arresters used in permanent buildings are class B, C and D arresters, fig. (5.9); they are installed at the junction of lightning protection zones. The building to be protected can be divided up into such zones to comply with the lightning protection zone concept.

The most stringent requirements of discharge capability are imposed on class B arresters. They are installed at the interface between lightning protection zones 0 and 1, as part of the lightning and overvoltage protection system, fig. (5.7 and 5.9).

These arresters must be capable of carrying several times the lightning branch currents of waveform 10/350 μs without being destroyed. The function of these lightning arresters is to prevent lightning branch currents from entering the electrical installation in a building.

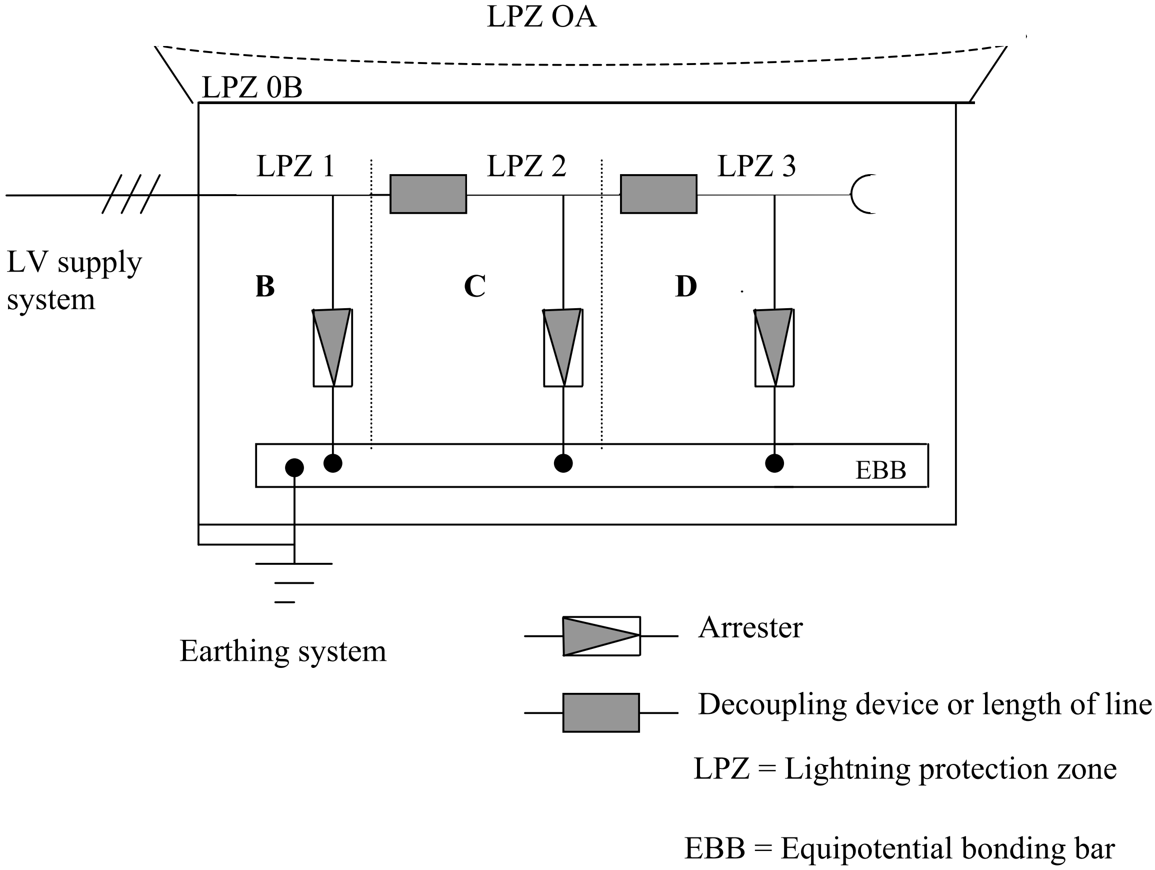

Fig. (5.9) dividing the building into different lightning protection zones with arresters in place

In case of maximum loading (protection level I), a current of 200 kA max. (waveform 10/350 μs) is likely to enter the building. If, in the worst possible case, only the ac-power network is available, the power circuit is loaded with 200 kA (10/350 μs). If once again worst-case conditions exist here in the form of two conductors (L, PE/N), the load amount to 100 kA (10/350 μs) for each conductor.

At this stage, attention should be paid to the “ PE/N lightning current Arrester ” fitted between the N and PE conductors in the TT systems. This arrester must be able to carry the total current of 200 kA (10/350 μs) that flows through the individual arresters between L and N without being destroyed.

Overvoltage arresters of class C are installed at the point where lightning protective zone 1 becomes zone 2 to protect the system from overvoltages that appear between line conductors and N as well as PE conductor.

The outer conductors (L1, L2 and L3) of the mains power system are as a rule equipped with arresters to provide protection. In mains system, in which the N conductor is routed separate from the PE conductor (TT and TN-S system); the arrester should be installed to the N conductor as well.

The final stage of lightning and overvoltage protection is the terminal unit protection provided at the point where lightning protection zone 2 changes to zone 3. The main function of these class D arresters used at this point is to provide protection against overvoltages that appear between line and neutral. This stage is generally implemented at the main input of communications power supply systems (rectifiers) and usually consists of zinc-oxide varistors.

5.5 Special Requirements for Lightning Protection in Telecommunication Towers

Usually the power supply installation for the transmission system is in the operating building beside the base of the tower, and the very long power supply conductors introduce the risk of induced overvoltages.

A lightning stroke on a telecommunication tower produces a very large voltage drop in the steel reinforcement. The overvoltage is thus produced in the cable and may damage the input circuit of the D.C. /D.C. converter. To avoid this, the following protective measures must be adopted:

-The D.C. Cables between the operating building and the base of the tower should be run in a metal tube. This tube is ‘ galvanically ’ connected to the reinforcement of the tower and the operating building and also, via a special cable duct in the operating building, to the battery switch panel.

Ensure that the tower and the building including the power supply system, are always at approximately the same potential with respect to the ground.

The d.c. power supply conductors between the battery switching panel in the operating building and the operating floor in the telecommunications tower should be in the form of screened cables.

The shortest route to the structural metalwork of the switching panel, the steel tube cable duct and the base of the tower should connect the screen of the cable.

Also the floor mesh earth should be bonded. By these expedients the ground resistance is reduced considerably.

Overvoltages, which exceed the permissible level in spite of the measures described above, are limited on the operation floor by means of the lightning-protection assembly.

Chapter 6

6 Impulse Testing of Electrical Equipment

Industrial and economic development in the present world demands the use of more and more electrical energy, which has to be transported over long distances in large quantities.

This very fast development of power systems should be followed by system studies on equipment and service conditions, which they have to fulfill. These conditions will determine the values of test voltages of a.c. power frequency, impulse, or d.c. under specific conditions.

High voltage laboratories are essential for making acceptance tests for the equipment that go into operation in the extra high voltage transmission systems, or equipment forced to operate in the overvoltage conditions due to lightning discharges and switching operations.

A high voltage laboratory is expected to carry out withstand and / or flashover tests at high voltages on the following transmission system equipment:

i. Transformers
ii. Lightning arresters
iii. Isolators and circuit breakers
iv. Different types of insulators
v. Cables
vi. Capacitors
vii. Line hardware and accessories
viii. Other equipment like reactors, etc.

Tests conducted on the above equipment are:

i. Power frequency withstand tests
ii. Impulse tests
iii. D.C. withstand tests
iv. Switching surge tests, etc.

In this chapter both impulse voltage and impulse current tests, only, on transformers and surge diverters, are discussed in details.

6.1 Importance of impulse testing

Impulse testing is necessary:

- To ensure that the electrical equipment is capable of withstanding the overvoltages that are met with in service.
- To ensure a reliable service for systems built by these tested equipment.

The overvoltages may be due either to natural causes such as like lightning or system originated ones such as switching and faults.

6.2 Generation of Impulse Voltages

6.2.1 Standard Impulse Waveshape

The lightning overvoltage can be represented by the double exponential wave defined by the equation

$$V(t) = V_o\,[\exp(-\alpha t) - \exp(-\beta t)] \qquad (6.1)$$

Where V_o = factor that depends on the peak value.
α and β are constants of microsecond values that control the front and tail times of the wave respectively.

The general waveshape is given in fig. (6.1). Impulse waves are specified by defining their rise time, tail time to 50% peak value and the value of the peak voltage.

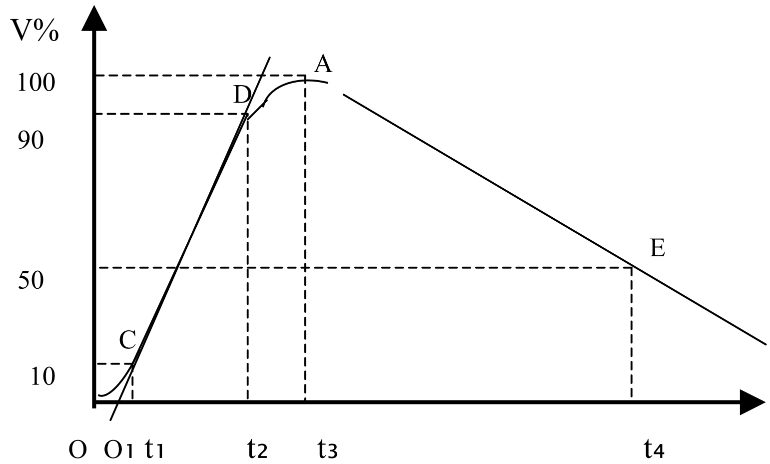

Fig. (6.1) Impulse waveform and its definition

Referring to fig. (6.1), the peak value *A* is fixed and referred to as 100% value. The point corresponding to 10% and 90% of peak value are located at points *C* and *D,* 1.25 times the interval between t_1 and t_2 is define as the front time, i.e. 1.25 ($0_1 t_2 - 0_1 t_1$)

The point *E* located on the wave tail corresponding to 50% of the peak value, the interval $0\,t_4$ is defined as the tail time.

6.2.2 Theoretical Representation of Impulse Waves

The impulse waves are generally represented by the double exponential waves defined by equation (6.1).

For impulse wave of 1.2/50 μs, α = - 0.0146, β = - 2.467 and Vo = 1.04 when time is expressed in microsecond.

6.2.3 Circuit for Producing Impuse voltage

Adouble exponential waveform of the type mentioned in Eq. (6.1) may be produced in the laboratory with a combination of a series *R-L-C* circuit under overdamped condition or by the compnation of two *R-C* circuits. Fig. 6.2a to d are commonly used.

Circuit shown in Fig. 6.2a is limited to model generator only, and commercial generators employ circuit shown in Fig. 6.2b to 6.2d.

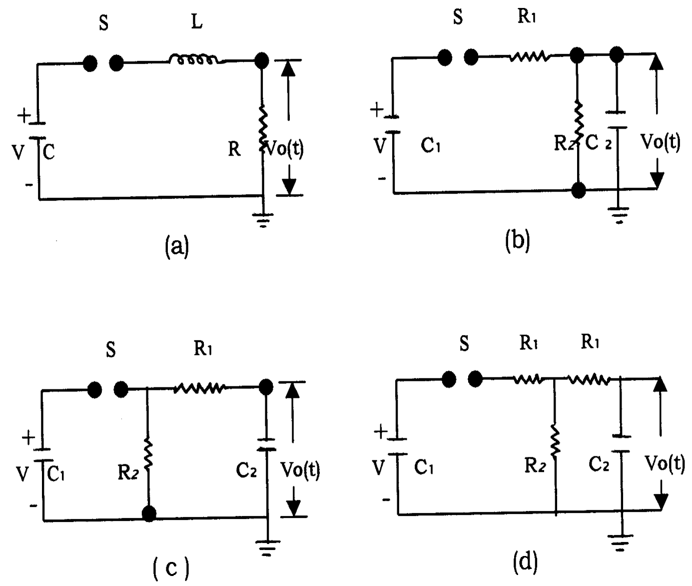

Fig. (6.2) Circuit for producing impulse waves

A capacitor (C_1 or C) previously charged to a particular d.c. voltage is suddenly discharged into the waveshaping network (*LR*, $R_1R_2C_2$ or other combination) by closing the switch *S*. The discharge voltage *Vo(t)* shown in fig. 6.2 gives rise to the desired double exponential waveshape.

By analysis of the impulse generator circuit of series *RLC* type, the solution of the equation for Vo(t), can be obtained i.e. finding the roots α (wave tail time) and β (wave front time).

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$$\alpha = -R/2L + \sqrt{(R/2L)^2 - 1/LC}$$
$$\text{and } \beta = -R/2L - \sqrt{(R/2L)^2 - 1/LC} \quad (6.2)$$

α and β are controlled by changing the values of R and L simultanously with a given generator capacitance.

6.2.4 Multistage Impulse Generators – Marx Circuit

For producing very high voltages, a bank of capacitors are charged in parallel and then discharged in series. The arrangement for charging the capaciors in parallel and then connecting them in series for discharging was originally proposed by Marx. The schematic diagram of Marx circuit and its modification are shown in fig. (6.3a) and (6.3b), respectively.

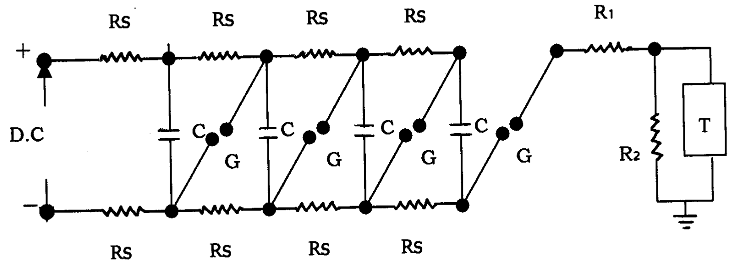


Fig. 6.3a Schematic diagram of Marx circuit arrangement for multistage Impulse Generator
C – Capacitance of the generator
RS – Charging resistors
G – Spark gap
R1, R2 – Wave shaping resistors
T – Test object

In the Marx circuit of fig. 6.3a the impulse wave shaping circuit is connected externally to the capacitance unit. In Fig. 6.3b, the modified Marx circuit is shown, wherein the resistances R_1 and R_2 are incorporated inside the unit. R_1 is devided into n parts equal to R_1/n and put in series with the gap G. R_2 is also devided into n parts and arranged across each capacitor unit after the gap G. This arrangement saves space. reduses the cost and icreases the efficiency (V_o / nV).

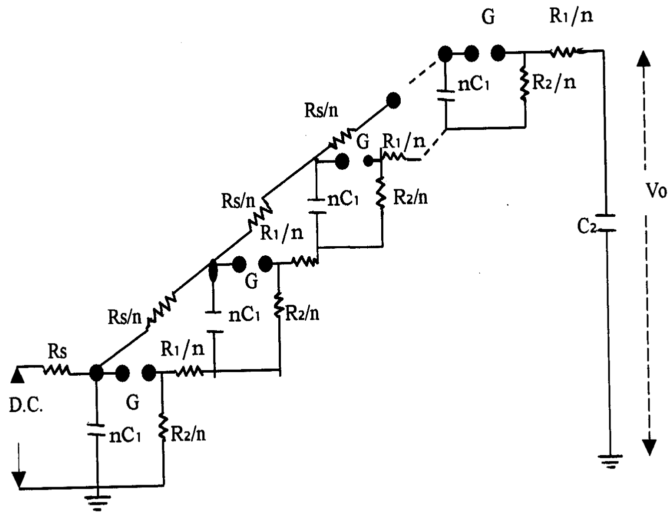


Fig. 6.3b Multistage impulse gen. incorporating the series and wave tail resistances within the generator

6.3 Generation of Impulse Currents

Lightning discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gears like surge diverters have to discharge the lightning current safely. Therefore, generation of impulse current waveforms of high magnitude (≈ 100 kA peak) find application in testing work as well as electric arc studies, and studies relating to electric plasmas in high current discharges.

6.3.1 Impulse Currents waveforms

The waveshapes used in testing surge diverters are 4/10 and 8/20 μ s, the figures respectively representing the nominal wave front and wave tail times (see Fig 6.1). The tolerances allowed on these times are ± 10% only. The duration of the wave is defined as the total time of the wave during which the current is at least 10% of its peak value.

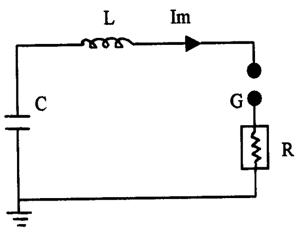
6.3.2 Generation of High Impulse Currents

For producing large values of impulse currents, a number of capacitors are charged in parallel and discharged in parallel into the circuit. The arrangement of capacitors is shown in Fig. 6.4c. In order to minimize the effective inductance, the capacitors are subdivided into smaller units.

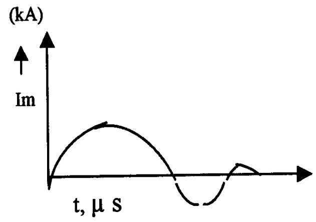
Also, the arrangement of capacitors into a horse-shoe shaped layout minimizes the effective load inductance.

The essential parts of an impulse current generator are:

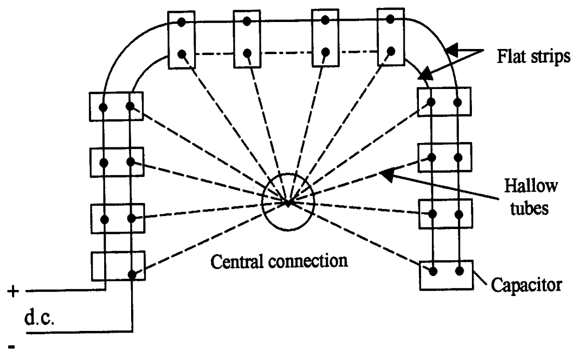
1- a d.c. charging unit given a variable voltage to the capacitor bank.
2- capacitors of high value (0.5 to 5 μF) each with very low self-inductance.
3- an additional air cored inductor of high current value.
4- Proper shunts and oscillograph for measurement purposes, and
5- a triggering unit and spark gap for the initiation of the current generator.



(a) Basic circuit of an impulse Current generator.



(b) Impulse current Waveform



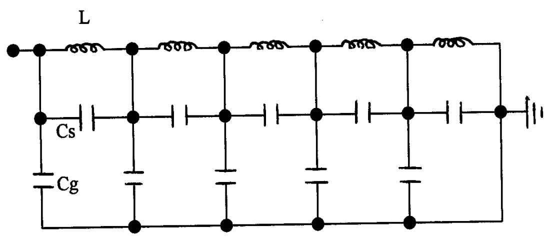
(c) Arrangement of capacitors for high impulse current generation

Fig. 6.4 Impulse current generator circuit and its waveform

6.4 Impulse Testing of Transformers

The purpose of the impulse tests is to determine the ability of the insulation of the transformers to withstand the transient overvoltages due to lightning, etc. The equivalent circuit of transformer winding for impulse is shown in Fig. 6.5. If an impulse wave is applied to such a network, the voltage distribution along the element will be uneven, and oscillations will be set in producing voltage much higher than the applied voltage.

Impulse testing of transformers is done using both the full wave and the chopped wave of the standard impulse, produced by a rod gap with a chopping time of 3 to 6 μ s. To prevent large overvoltages being induced in the winding not under test, they are short circuited and connected to ground. But the short-circuiting reduces the impedance of the transformer and hence poses problems in adjusting the standard waveshape of the impulse generators. It also reduces the sensitivity of detection.



L - Inductance (series)
Cs - Series capacitance
Cg - Shunt capacitance to ground

Fig. 6.5 The equivalent circuit of transformer winding for impulse

6.4.1 Procedure for Impulse Testing

The schematic diagram of the transformer connection for impulse testing is shown in Fig. 6.6, and the waveshapes of the full and chopped wave are shown in Fig. 6.7. In transformer testing, it is essential to record the waveforms of the applied voltage and current through the windings under test.

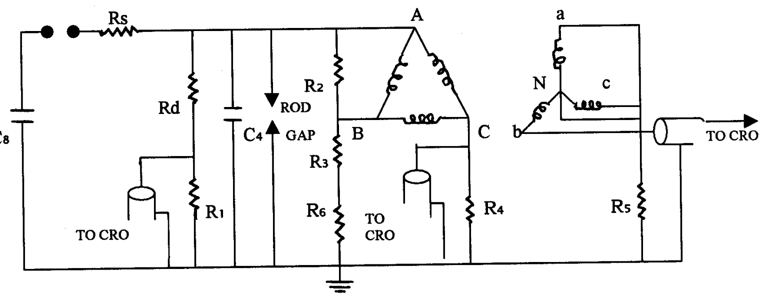


Fig. 6.6 Arrangement for transformer of impulse testing

Impulse testing is done in the following sequence:

1- applying impulse voltage of magnitude 75% of the Basic Impulse level (BIL) of the transformer under test.
2- one full wave voltage of 100% BIL.
3- two chopped wave of 115% BIL.
4- one full wave of 100% BIL. and
5- one full wave of 75% BIL.

It is very important to see that the grounding is proper and the windings not under test are suitably terminated.

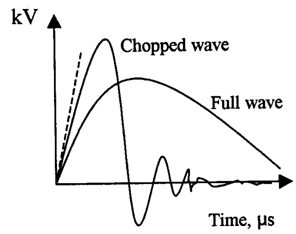


Fig. 6.7 Full wave and chopped wave

6.4.2 Detection and Location of Fault during Impulse Testing

The fault in transformer insulation is located in impulse tests by any one of the following methods:

General observations

The fault can be located by general observations like noise in the tank or smoke or bubbles in breather.

Voltage oscillogram method

Fault appears as a partial or complete collapse of the applied voltage wave. Fig. 6.8 gives the typical waveform. The sensitivity of this method

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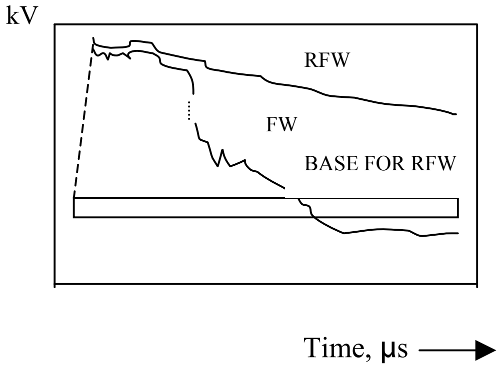
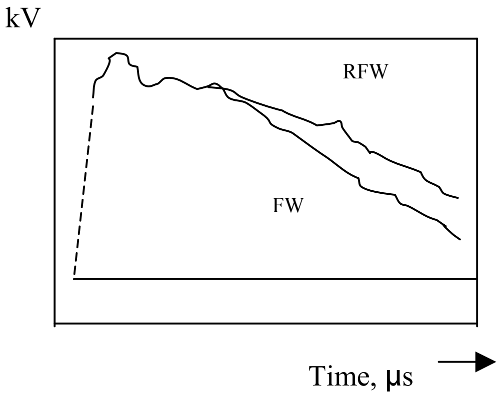
is low and does not detect faults, which occur on less than 5 % of the windings.



(a) Failure from line lead to ground through oil



(b) 8.5% of winding failed

Fig. 6.8 Voltage oscillogram of transformer winding with a fault
RFW- Reduce full wave
FW- Full wave

3. Neutral current method

In the neutral current method, a record of the impulse current following through a resistive shunt between the neutral and ground point is used for detecting the fault.

When a fault occurs on the neutral current oscillogram, such as arcing between the turns or from turns to ground, atrain of high frequency pulses similar to that in the front of the impulse current wave are observed in the oscillogram and the waveshape changes.

4. ***Transferred surge current method***

In this method, the voltage across a resistive shunt connected between the low voltage winding and the ground is used for fault location.

A short high frequency discharge oscillation is capacitively transferred at the event of failure and is recorded. Hence, faults at further distance from the neutral are also clearly located.

The waveshape is distorted depending on the location and type of fault, and hence can be more clearly detected.

6.5 High Current Impulse Test on Surge Diverters

A high current impulse wave of 4/10 μs and of peak value e.g. 100kA is applied to a surge diverter to be tested.

The diverter is said to have passed the test, if

1- the power frequency sparkover voltage before and after the application of the current wave does not differ by10%.
2- the voltage across the diverter at the first and last application of the current wave does not differ by more than 8%.
3- there is no sign of puncture or other damage.

Chapter 7

6 Conclusions

The object of this study is to high-light the importance of lightning protection systems for structures and electrical equipment.

Lightning destroys billions of dollars every year through its disastrous effects on structures and electrical equipment.

Protection of structures against lightning is based on a probabilistic assignment, which takes the following factors into account:

- Soil resistivity.
- The external dimensions of the structure and any electrically connected adjacent structures.
- The length of overhead cables emanating from the structure.
- The lightning flash density in the locality associated with thunderstorm days per year.
- The construction type such as height, type of roof, etc.
- Geographic factors: height above sea level and relation with other structures, i.e. how close it is to other structures and tall trees.
- Ground profile and terrain.

All these factors are taken into account when calculating the risk factor of the strike.

If the risk is less than 1 in 100,000, then generally no protection is required. However, in order to carry out formal risk assignment, this needs to be assessed in relation to the consequences of a direct strike.

If a building is associated with an oil refinery or houses explosives, then a lightning protection scheme offering the highest possible degree of protection will be required, even if the risk of a strike is small.

The overall design of a lightning protection system is based on the concept of a rolling sphere, which is applied to the structure to ensure that all exposed areas are protected by the scheme.

The materials used are generally high purity copper or aluminuim of a similar grade to that used for electrical conductors.

The lightning protection system must be designed to provide sufficiently low impedance that the lightning energy will follow the required route. This requires so an integrated design and use of materials with sufficiently low impedance.

If a lightning protection system is fitted to a structure or electrical equipment and correctly installed with approved materials, the risk of damage is likely to be minimal. However, because of the nature of lightning, it is impossible to guarantee total protection.

The proximity and magnitude of indirect strikes determine whether any damage to the actual building or structure occurs. It was found that there is a great chance for indirect strikes to travel into the building via power supply cables or telecommunication or signal cables.

The induced voltage spikes cause damage to some or all of the sensitive electronic equipment housed within the building. Surge protection units should be installed to protect this equipment.

APPENDIX (A)
Materials used and Specifications

Table (A1)

Recommended materials for the manufacture of lightning protection components

Material and processes	BS No.	Grade or Type
Ingots for cast components		
Leaded gunmetal	BS 1400	LG1,LG2
Aluminium silicon bronze	BS 1400	AB1.AB3
Aluminium alloy	BS 1490	LM6M,LM25
Cast iron	BS 1452	220,250
Malleable iron	BS 6681	-
Forgings and stampings		
Copper	BS 2872	C101/2/3S
Naval brass	BS 2872	CZ112
Aluminum	BS 1474	6082TF
Steel	BS 970: Part 1	All grades
Bars, rods and tubes (for machined components and fittings)		
Hard down copper	BS 2874	C101/2/3
Copper silicon	BS 2874	CS101
Aluminum	BS 1471	6082TF
Steel	BS 970:Part 1	All grades
Stainless steel	BS 970:Part 1	-
Nuts, bolts, washers, screws and rivet fixing for use on copper		
Phosphor bronze	BS 2874	PB102-M
Naval brass	BS 2874	CZ112 CZ132
Copper silicon	BS 2874	CS101
Nuts, bolts, washers, screws and rivet fixing for use on Aluminium		
Alloy	BS 1473	6082
Stainless steel	BS 3111: Part 2	
Galvanized steel	BS 3111: Part 1	
Solid rounds, flats and strand conductor		
Copper		
Hard down copper	BS 1433	C101/2/3
Copper (stranded)	BS 6360	Insulated
Copper (flexible)	BS 6360	-
Aluminium		
Aluminium strip/rod	BS 2897	1350
Aluminium alloy	BS 3242	-
Steel		
Galvanized steel	BS 302: Part 2	-
Galvanized strip	BS 302: Part 2	-

Pressing and fabrication (for strip, coil and sheet)		
Annealed copper	BS 2870	C101/2/3
Aluminum	BS 1474	6082TF
Stainless steel	BS 1449: Part 2	316S12

Table (A2)

Minimum dimension of component parts

Component	**Dimension (mm)**	**Area (mm²)**
Air terminations:		
Aluminium, copper and galvanized steels trip	20x2.5	50.0
Aluminium, aluminium alloy, copper Phosphor bronzes and galvanized steel rods	8.0 dia.	50.0
Suspended conductors:		
Stranded aluminium	7/3.0	50.0
Stranded copper	19/1.8	50.0
Stranded aluminium (steel reinforced)	7/3.0	50.0
Stranded galvanized steel	7/3.0	50.0
Down conductors:		
Aluminium, copper and galvanized steel strip	20x2.5	50.0
Aluminium, aluminium alloy, copper Phosphor bronze and galvanized steel rods	8.0 dia.	50.0
Earth terminations:		
Austenitic	14.0 dia.	153.0
Copper and galvanized steel strip	20x2.5	50.0
Copper and galvanized steel rods	8.0 dia.	50.0
Hard down copper rods for direct driving into soft ground	8.0 dia.	50.0
Rods for hard ground	12.0 dia.	113.0
Driving or laying in ground	8.0 dia.	50.0
Copper-clad for harder ground	14.0 dia.	153.0
Fixed connections (bond) in Al, Al. alloy, Cu and galvanized steel		
External strip	20x2.5	50.0
External rods	8.0 dia.	50.0
Internal strip	20x1.5 dia.	30.0
Internal rods	6.5 dia.	33.0
Flexible or laminated connections (bonds)		
External, aluminium	20x2.5	50.0
External, annealed copper	20x2.5	50.0
Internal, aluminium	20x1.5	30.0
Internal, annealed copper	20x1.5	30.0

APPENDIX (B)

A Sample Calculation of overall Risk Factor

The items in tables B1, B2, B3, B4 and B5 in BS 6651 are termed ‘ the weighting factor values.’ They denote a relative degree of importance in each case.

Table (B1)

Weighting factor A (use of structure)	
Use to which structure is put	**Value of factor A**
House and other buildings of comparable size	0.3
House and other buildings of comparable size with outside aerial	0.7
Factories, workshops and laboratories	1.0
Office blocks, hotels, blocks of flats and other residential buildings other than those included below	1.2
Places of assembly, e.g. churches, halls, theaters, museums, exhibitions, department stores, post offices, stations, airports and stadium structures.	1.3
Schools, hospitals, children’s and other homes	1.7

Table (B2)

Weighting factor B (type of construction)	
Type of construction	**Value of factor B**
Steel frame encased with any roof other than metal	0.2
Reinforced concrete with any roof other than metal	0.4
Steel frame encased or reinforced concrete with metal roof	0.8
Brick, plain concrete or masonry with any roof other than metal thatch	1.0
Timber framed or clad with any roof other than metal or thatch	1.4
Brick, plain concrete, masonry, timber framed but with metal roofing	1.7
Any building with a thatched roof	2.0

Table (B3)

Weighting factor C (contents or consequential effects)	
Contents or consequential effects	**Value of factor C**
Ordinary domestic or office buildings, factories and workshops Not containing valuable or specially susceptible contents	0.3
Industrial and agricultural buildings with specially susceptible contents	0.8
Power stations, gas installations, telephone exchanges, radio stations	1.0
Key industrial plants, ancient monuments and historical buildings, museums, art galleries or other buildings with specially valuable contents	1.3
Schools, hospitals, children’s and other Homes, place of assembly	1.7

Table (B4)

Weighting factor D (degree of isolation)	
Degree of isolation	**Value of factor D**
Structure located in large area of structure or trees of the same or grater height, e.g. in a large town or forest	0.4
Structure located in an area with few other structures or trees with similar height	1.0
Structure completely isolated or exceeding at least twice the Height of surrounding structure of trees	2.0

Table (B5)

Weighting factor E (type of country)	
Type of country	**Value of factor E**
Flat country of any level	0.3
Hill country	1.0
Mountain country between 300m and 900m	1.3
Mountain country above 900m	1.7

Table (B6)

Relationship between thunderstorm days per year And lightning flashes per km² per year

Thunderstorm days per year	Flashes per km² per year	
	Mean	Limit
5	0.2	0.1 to 0.5
10	0.5	0.15 to 1
20	1.1	0.3 to 3
30	1.9	0.6 to 5
40	2.8	0.8 to 8
50	3.7	1.2 to 10
60	4.7	1.8 to 12
80	6.9	3 to 17
100	9.2	4 to 20

The data for this table has been extracted from information in Anderson, R.B. and Eriksson, A.J. (Conference Internationale des Grands Reseaux Electriques (CIGRE)) Lightning Parameters for Engineering Application.
Electra, 1980, **69**, 65 – 102.

For example:

Consider the SUDATEL H.Q. building in Khartoum with brick walls and reinforced concrete frame, consists of valuable importance equipment, located in area of structures at similar and different heights, where the dimensions of the building are:

Length = 43.6m
Height = 40.4m
Width = 27.6m

The risk factor can be calculated as follow using the map of fig. (4.2) and the above tables.

Step 1

Determine the number of flashes to ground per km squared per year (Ng). (From the map and table B6 taken the mean value = 0.5).

Step 2

Determine the collection area (Ac) of the building, which is simply the products of:

$$
\begin{aligned}
Ac &= LW + 2LH + 2WH + \pi H^2 \\
&= (43.6 \times 27.6) + 2(43.6 \times 40.4) + 2(27.6 \times 40.4) + \pi \times 40.4^2 \\
&= (1203.36) + (3522.88) + (2230.08) + 5124.98 \\
&= 12081.3
\end{aligned}
$$

Step 3

Determine the probability of being struck (P).

Where $P = Ac \times Ng \times 10^{-6}$

$$
\begin{aligned}
&= 12081.3 \times 0.5 \times 10^{-6} \\
&= 0.00604065
\end{aligned}
$$

Step 4

Applying the relevant weighting factors from (Tables B1, B2, B3, B4 and B5).

Factor $A = 1.2$
$B = 0.4$
$C = 1.3$
$D = 0.4$
$E = 0.3$

The overall weighting factors = $A \times B \times C \times D \times E = 0.07488$

Step 5

Therefore, the overall risk factor
= (Probability of being struck) x (overall weighting factor)
= $0.00604065 \times 0.07488$
≈ 0.00045

Or expressing this answer as a reciprocal we obtain 1 in 2222.

As the 10^{-5} (1 in 100,000) is the criteria for determining whether protection is necessary or not, we can see that 1 in 2222 is "shorter odds" and so protection is essential.

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